

# Requirements for Industrial Symbiosis by cluster development for by-product hydrogen and regional hydrogen mobility

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# Requirements for Industrial Symbiosis by cluster development for by-product hydrogen and regional hydrogen mobility

## An Explorative Case Study

By

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An emerging strategy for industry to reduce environmental impact is the utilization of by-products. Steel manufacturer Tata Steel IJmuiden in the Netherlands has identified a large potential source of by-product hydrogen inside a waste stream gas from cokes production, a process that lies at the heart of the steel making process. A possible market for such a novel source is regional hydrogen mobility, which is one of two zero-emission mobility options needed to reach climate goals. However, hydrogen mobility is currently in its infancy, applications are costly and development is complex. Also, alternative sustainable hydrogen sources are inefficient and not competitive with hydrogen produced from fossil sources. This research therefore proposes that by-product hydrogen could be a transitional source of hydrogen during market development of hydrogen mobility. A study in the US found that utilizing by-product hydrogen from the steel industry for hydrogen mobility can result in positive well-to-wheel energy efficiency and environmental gains.

The aim of this research is to explore the requirements for developing regional hydrogen mobility with a by-product source of hydrogen from the steel industry. An emerging scientific field that can aid to do so is Industrial Symbiosis, which focuses on revalorization and utilization of by-products. Several models for the development of industrial symbiosis have been proposed, however none have looked into the use by-products for regional mobility development. A steel company can build the necessary technology and infrastructure on its terrain, however a hydrogen mobility market will not form itself. Therefore, in extension to the industrial symbiosis approach, this research uses the cluster approach. It is argued that in a globalising economy, clustering is necessary in order to achieve competitive advantage, an imperative for market development. Clustering focuses on *how* companies compete, and leads to productivity benefits, innovation benefits and the formation of new businesses, all relevant to the research aim.

Based on these concepts, the research question for the thesis was “*How can industrial symbiosis of by-product hydrogen from the steel industry contribute to regional hydrogen mobility by cluster development during transition to zero-emission mobility?*” First, the question was asked how various scientific concepts of industrial symbiosis and clustering could be combined in order to form a general framework of requirements and related indicators. This framework was then applied to the case study of Tata Steel IJmuiden and the province of Noord Holland. Apart from scientific literature, information was gathered by explorative interviews with experts, attending meetings and studying publications, leading to a broad set of requirements and finally recommendations for the steel company based on a systems perspective.

As the concepts of industrial symbiosis and clustering showed overlap, combining them was possible. This allowed for a broad scope for analysis of requirements

specifically for by-product hydrogen from the steel industry and hydrogen mobility. Mostly the model showed that cluster development is a complex process requiring not only technology and infrastructure, but additional institutional layers, policies and collaboration.

Technologically, realizing a cluster was found to be possible, and by-product hydrogen delivered by the steel company can potentially be economically competitive with other sources, and able to provide at least on third of regional potential hydrogen demand. As a regional cluster approach takes into account all sources, an existing source of hydrogen was found that could be used during initial stages of market development to prevent high initial investment costs related to by-product separation. From an institutional perspective, clustering for hydrogen mobility was found to be currently happening through a National Hydrogen Platform. Currently the platform is in a relatively early stage, and showed clustering is happening on a national level rather than regionally. Importantly, regional policy in Noord Holland was found to be favourable towards zero-mobility, but the province has lost interest in hydrogen. It was found to be mostly up to transportation companies to choose their type of mobility and infrastructure, the province merely sets boundary conditions for zero-emission.

Initially, public funding will be needed to finance the obstacles related to market preparation. Creation of an entity or “coalition of the willing” of industry partners is found to be favourable during early stages, which acts as a legal counterpart for the government that shows commitment in return for public funding. Establishment of a network of trust, collaboration and the sharing of knowledge are influential factors, for which public-private partnerships such as so-called ‘Green Deals’ can assist. Building the capacity to mobilize development in such a network may take many years of relationship building and joint production of knowledge. Several drivers are the strategic location of Tata Steel IJmuiden near potential urban markets, Schiphol airport and main highways identified by European initiatives as favourable initial refuelling station locations.

Predominantly, this research has provided an overview of the requirements and important factors needed in order to develop such a configuration. It is based on several assumptions, one of which is that energy efficiency and environmental gains could be achieved. An important question remains whether utilizing a by-product from a waste gas stream that originates from a process with coal as a main input is desirable from an environmental perspective during transition to zero-emission mobility, and should be further investigated.



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## Introduction

Trends in energy supply and transport and mobility are currently unsustainable – socially, environmentally and economically. Technologies are still for the largest part based on fossil fuels, and with a growing population, progressive industrialisation and urbanisation energy demand is expected to rise rapidly. Consensus is growing that corresponding greenhouse gas (GHG) emissions need to be reduced if dangerous climate change effects are to be mitigated.

In order to reduce the impact of climate change and reach ambitions of national and European CO<sub>2</sub> emission reductions, there is a pressing need to accelerate the implementation of zero emission mobility technologies. Mobility is responsible for 23 percent of CO<sub>2</sub> emissions in the Netherlands, 62 percent of the total NO<sub>x</sub> and 31 percent of particulate matter (CBS, 2014). The mobility system therefore requires the adoption of alternative drive train vehicles which currently lead to two options: Battery electric vehicles (BEV) or Fuel Cell Electric Vehicles (FCEVs), as they do not require fossil fuels, but run on electricity and hydrogen respectively. There is ongoing debate as to which is the preferable option, however consensus is growing towards both technologies being complementary in contrast to merely competitive.

In 2015 the International Energy Agency (IEA) published a technology roadmap for hydrogen and FCEVs, in which they uncover several cross-cutting advantages and opportunities. Hydrogen is a flexible energy carrier and can be applied in a wide range of end-use applications, including hydrogen buses, personal vehicles, forklifts and many more. Other advantages include the potential of significantly reducing energy related CO<sub>2</sub>-emissions and lowering local air pollutants and noise emissions in comparison to direct fossil fuel combustion (IEA Technology Roadmap, 2015). Importantly, fuel cell technology is said to be currently technically ready for commercialization, and applications are expected to get closer to cost-competitive range within the next decade (Ball & Weeda, 2015).

However, despite all possible advantages related to the uptake of hydrogen technologies, widespread deployment remains absent. Important barriers are currently the costs of fuel cells, production methods and the development of a hydrogen transmission and distribution network. Steps need to be made in developing cost efficient hydrogen generation (IEA Technology Roadmap, 2015). Hydrogen is currently mainly produced using fossil fuels as inputs for various processes of production. Steam methane reforming contributes the most, a two-step

process that uses natural gas and H<sub>2</sub>O for production. The current main 'green' source of hydrogen is known as electrolysis, which produces hydrogen from electricity and H<sub>2</sub>O. As electrolyzers are predominantly connected to the electricity grid and not directly to renewable energy sources (such as solar or wind energy), they can also be seen as ultimately a fossil derived source of hydrogen, and are currently not cost-efficient.

Interestingly, hydrogen also occurs as a by-product in various industrial processes such as the steel industry, posing an opportunity. As industries are currently under pressure to reduce their emissions and environmental impact, a possible measure is the utilization of such a by-product. Hydrogen is generated as part of a waste gas stream during the coke production process, which lies at the heart of modern day steel production. The gas (coke oven gas, COG) contains a wide variety of chemicals such as methane, nitrogen and carbon monoxide, but in volume percentage the largest component is hydrogen. Globally, these streams make up approximately 8.0 EJ per year (IEA Technology Roadmap 2015). Joseck, Wang & Wu (2008) studied the potential energy and greenhouse gas emission effects of hydrogen production from COG in US steel mills on a well-to-wheel basis, and found significant energy and GHG emission reductions could be achieved. Interestingly, by-product hydrogen (where available) and existing production capacities is said to be the main initial source of hydrogen supply, and that arguably related hydrogen infrastructure should precede large scale FCEV rollout (Ball & Weeda, 2015). This way a regional source and infrastructure could stimulate a regional hydrogen mobility market and decrease the chicken and egg dilemma of hydrogen infrastructure and mobility applications. These findings indicate an opportunity for both zero-emission hydrogen mobility and the pressures on industry to reduce its environmental footprint, making it an interesting option to pursue.

## 1.1 Tata Steel IJmuiden

Such a by-product hydrogen source was uncovered in the province of Noord Holland in the Netherlands. Steel manufacturer Tata Steel IJmuiden (TSIJ) produces cokes as inputs for the steel making process with a resulting waste stream COG of 14 PJ, containing up to 60 volume percentage of hydrogen. Should the hydrogen be separated, this would lead to a novel regional hydrogen source of over 35,000 tonnes per year. To put this into perspective, such a source would be sufficient to fuel over 3 million personal FCEVs annually (CBS, 2015; Vishnyakov, 2006).

Part of the waste stream COG (2 PJ) is currently distributed to neighbouring energy firm Nuon for electricity production, and the main part (12 PJ) is used for heating furnaces on-site. Initial discussions have been ongoing concerning opportunities related to hydrogen contained in the COG, and several in-company research papers have been written related to necessary technology or economic implications. Several findings, especially regarding technology needed on-site have been found to be possible, however practical implementation or concrete action towards development

of such an opportunity remain absent. Tata Steel IJmuiden is currently exploring options to enter the hydrogen market, starting hydrogen mobility as main application as this is gaining public interest. However, as the company is a steel manufacturer, entering the gas market with a by-product is far from their core-business. The company could build the needed infrastructure on-site up to their fence, but a currently infant market for hydrogen mobility is not expected to form itself as a result of a novel regional hydrogen source. Hence, distributing it over the fence requires a broad scope of information and novel approaches to such a complex opportunity.

## 1.2 Scientific approaches

This research is concerned with the development of by-product hydrogen as a potential source and hydrogen mobility as potential market. A field of research aimed at uncovering potential and practical implementation of by-products is known as **Industrial Symbiosis** (IS). This is seen as the process by which by-products are revalorized and exchanged among traditionally separate business entities, and can bring, financial, social and environmental benefits to firms and society (Yap, 2016). The concept focuses on the flow of materials and energy, and the keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity (Chertow 2000). The organisation for economic cooperation and development (OECD) has shown specific interest in the development of IS, as it is recognized as an important innovation for green growth and for decreasing resource needs (OECD, 2012).

The concept is often viewed as a practical approach, and not only does it focus on the flow of energy materials and resources, but also takes into account the networks of businesses regionally and locally to achieve exchanges which are economically and ecologically sustainable for industrial development (Chertow, 2007). According to Chertow, the sharing of resources is not limited to physical linkages, and mentions three options for resource exchange: the reuse of by-products, sharing of infrastructure and/or utilities and the joint provision of services. In practice, when an industrial region displays a variety of IS linkages, it is commonly referred to as an **eco-industrial park** (EIP). The most obvious and common reason to pursue IS are conventional business reasons, meaning exchanging resources can lead to cost reductions or even increase revenues (Chertow, 2007). The widely cited definition that Chertow (2007) proposes is as follows:

*“The part of industrial ecology known as industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water and by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity.”*

Industrial symbiosis is not a new phenomenon, as it has been taking place long before the scientific field took shape, and mentions resource exchanges primitive people shared such as animal parts. As the definition states, it is rooted in **Industrial**

**Ecology** (IE), a scientific field associated with sustainability, and focuses on the interaction between natural systems (the biosphere) and industrial systems (technosphere). In this, researchers view the natural ecosystems as models for current industrial practices from which lessons can be learnt, and following this analogy, IE rejects the concept of waste not only in the biosphere but also in the technosphere. It promotes the view that industrial systems can reduce their impact on their natural environment, while at the same time improving their economic performance through efficient cycling of material and energy flows (Frosch and Gallopoulos, 1989; Lifset and Graedel, 2002). In other words, preserving the environment while increasing business value, which similar to IS is one of the main aims of Industrial Ecology.

As the stated problem spans further than the concept of by-product linkages, and requires an approach related to the realization of a competitive hydrogen mobility market with by-product hydrogen as a source. This lead to the theory of **clusters**, rooted in a view based on findings on new economics of competition in a global economy. This theory was found especially related, as Gibbs (2003) states that by definition the construction of EIPs and IS are heavily reliant on local and regional network of firms or “clusters”, which interact closely with one another.

Cluster theory argues that competitive advantage in a global economy lies increasingly in local factors such as knowledge, relationships and motivation that distant rivals are not able to match (Porter, 1998). In today’s world, companies are able to source goods, capital, information and technology globally, which instinctively leads to the thought that the role of local competitiveness is diminishing. However, upon asking the question why some regions such as the high-tech Silicon Valley or auto manufacturers in Germany prosper so much more than others in their particular fields, Porter argues the opposite. Instead, the economic map of today is dominated by critical masses in a particular region that demonstrate unusual competitive success. The definition of a **cluster** is given by Porter (1998):

*“A geographic concentration of interconnected companies and institutions in a particular field, and encompass an array of linked industries and other entities important to competition.”*

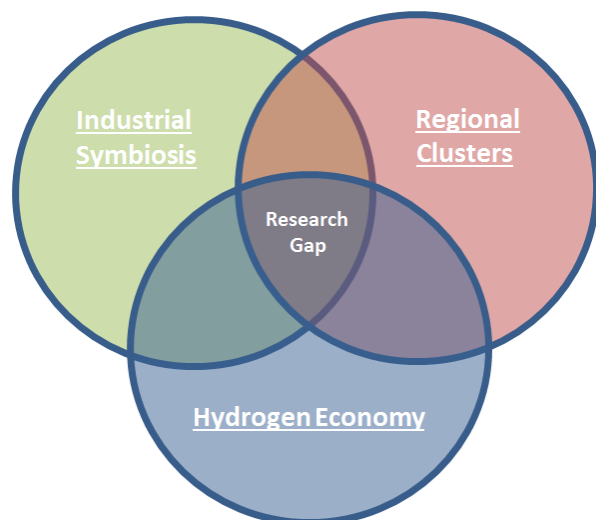
Clusters are critical to success as modern day competition relies on productivity and productivity growth, where the emphasis does not lie on the particular field of competition, but on *how* companies compete. Any industry can be competitive by adopting the newest technology or knowledge, but the sophistication with which companies compete is strongly influenced by the local business environment (Porter, 1998). Conversely, economic regions are defined by clusters, which may or may not be restricted to political boundaries – successful cluster examples may only cover a small area of a province, span several cities or even span over international borders (Padmore & Gibson, 1998). It is argued that every region has at least some industrial clusters, but not every concentration of firms can be viewed as a cluster. According to

a wide variety of authors (Porter, 2000; Padmore & Gibson 1998; Boons, 2008), clustering is a function of the number and quality of linkages among firms and with other elements of the local economy enabling innovation, competitiveness and other benefits.

### 1.3 The Research Gap

The various concepts discussed have a range of things in common. Industrial symbiosis is mostly concerned with sustainable practices and related benefits, and looks into requirements such as physical and social infrastructures needed to establish linkages, or policy measures to support development. This has been found to be applicable to by-product hydrogen in the steel industry. Alternatively, the theory of clusters has been found relevant to incorporate a broad scope and a regional focus to obtaining knowledge on requirements for development of a hydrogen mobility market using by-product hydrogen as a source of supply. One striking resemblance covering all notions and that may arguably be the most important feature of IS, EIP and cluster development, is the establishment of **networks**. When assessing literature, collaboration, interconnection and inter-firm networks are used frequently and are incorporated in all definitions. It is the essence of linkages and networks that make such sustainable initiatives span wider than a mere technical approach to the issue, adding a strong social dimension. It mainly refers to the need for firms to interact more extensively than required for normal business practice in order to develop industrial symbiotic linkages. Gertler (1995) explains it quite clearly: “because industrial symbiosis requires interaction and trust among companies that goes well beyond normal business practice, such expanded collaboration is both a component and a necessary precursor of industrial ecosystem development”.

When looking at the problem statement, it has a strong focus on sustainable development related to industrial symbiosis, and local competitiveness is required in order to reach the ultimate goal of hydrogen mobility market development using a by-product source. Both theoretical concepts of IS and clusters have a practical focus and show much overlap and share a broad or ‘systems’ perspective. However, no research on the combination of these theories and application to by-product hydrogen and hydrogen mobility has been performed. Therefore, findings can benefit both the academic field of industrial symbiosis and clusters. The combination can be a useful contribution



**Figure 1 The research gap, situated at the intersection of the theoretical fields industrial symbiosis and clusters, and the practical field of hydrogen mobility**

to gain knowledge on the practical development of what can possibly be an interesting opportunity for sustainable development for both industry and mobility. The research gap is therefore situated at the intersection between all fields: industrial symbiosis, clusters and hydrogen mobility (Figure 1).

## 1.4 Working definition

Based on the common notions of the concepts of industrial symbiosis, eco-industrial parks and clusters, a definition is proposed by the author. As the main resemblance is the formation of networks, this is used as a basic categorization in order to capture all elements. Networks cannot be reduced to one single definition, and can be both formed and categorized in a wide range of ways, and Wallner (1998) has made a useful categorization when forming a new industrial ecology. The relevant components of this categorization used shown in Table 1, and the categories of “intensity of the connection” and “temporal development” are left out as there were no aspects found in these categories for industrial symbiosis and clustering (Wallner, 1998).

**Table 1 Comparison of definitions based on network categorization (Wallner, 1999)**

<b>Network defined according to:</b>	<b>Industrial symbiosis</b>	<b>Eco-industrial Park</b>	<b>Cluster</b>
<b>Functional area of effect and objective of the networks</b>	<ul style="list-style-type: none"> <li>- Competitive advantage</li> <li>- eco-innovation</li> <li>- long term cultural change</li> <li>-improved business and technical processes.</li> <li>- mutually profitable transactions</li> </ul>	economic, environmental gains and human resource enhancement for business and local community	<ul style="list-style-type: none"> <li>-Competitive advantage</li> <li>-Business growth</li> </ul>
<b>Actors involved</b>	<ul style="list-style-type: none"> <li>-collaboration,</li> <li>-Engagement of traditionally separate industries</li> <li>- diverse organizations</li> </ul>	<ul style="list-style-type: none"> <li>-community of businesses</li> <li>-Inter-organisational Cooperation and with community</li> <li>-industrial users</li> </ul>	<ul style="list-style-type: none"> <li>-in a particular field</li> <li>-interconnected companies and institutions</li> <li>- linked industries and other entities</li> </ul>
<b>Exchange variables</b>	<ul style="list-style-type: none"> <li>-physical exchange of materials, energy, water and by-products</li> <li>-value-added destinations for non-product outputs</li> <li>- Creating and sharing knowledge</li> </ul>	Resource sharing	<ul style="list-style-type: none"> <li>-vertical and horizontal relationships</li> <li>-knowledge spill-overs</li> </ul>
<b>Spatial area of effect</b>	synergistic possibilities offered by geographic proximity		geographic concentrations geographically proximate firms
<b>Structure and organisation</b>	-Collective approach		-shared developmental vision

When placing various aspects of the previous concepts within the categorization, it shows apparent overlap. This makes it possible to combine the different definitions into a complete and aggregated definition of an *Industrial Symbiosis Cluster*:

*“A network of proximate institutions and diverse organisations from traditionally separate industries collaborating with a shared developmental vision to create physical non-product added-value, business growth and environmental gains for industry and the local community”*

## 1.5 Research Aim & Questions

The aim of this research is to uncover and gain insights on the main requirements and indicators for the development of by-product hydrogen from the steel industry for market development of regional hydrogen mobility. A broad scope is chosen as this research is seen as first step in an entirely new field, namely that of using by-products as inputs to the mobility system. Therefore, the purpose is mainly to provide an overview of the possibilities and requirements for development of such a construct. The concepts described provide a solid foundation to achieve this. Subsequently, the main research question is:

***How can industrial symbiosis of by-product hydrogen from the steel industry contribute to regional hydrogen mobility by cluster development during the transition to zero-emission mobility?***

The research question has been delineated into three sub-questions:

- 1) How can relevant concepts and models of industrial symbiosis and clusters be integrated into a coherent model of requirements and indicators?*
- 2) What are the requirements specifically for by-product hydrogen and regional hydrogen mobility based on a case study of Tata Steel IJmuiden and the Province of Noord-Holland?*
- 3) What recommendations can be made in regard to the case study for the current and future situation from a systems perspective?*

## Literature Review

This chapter presents all relevant models found by the author related to the concepts of industrial symbiosis and clusters. Especially the field of industrial symbiosis knows many forms, and as by-product hydrogen for mobility purposes is a new field of research, many models are related.

### 2.1 Models of Industrial Symbiosis

As this research seeks to find and combine the intersection between cluster development and the development or emergence of Industrial Symbiosis, models in this field will be analysed. In order to provide relevant insights, a categorization was made of different models, with the main distinction being either self-emerging (evolutionary) models or planned models of Industrial Symbiosis. These different perspectives are current source of debate within the field of Industrial Ecology.

#### 2.1.1 Self-organized models

Self-emerging or evolutionary models of Industrial Symbiosis arise mainly through evolutionary mechanisms rather than evolving from a grand plan. The main example of this is Kalundborg in Denmark, where a large Eco-Industrial Park has emerged with multiple symbiotic linkages without a formal planning authority or local government involved. According to Chertow & Lifset (2004), these symbiotic linkages or synergies emerged through participating companies striving to achieve economic goals. The main observation regarding self-organising is the absence of a third-party governing the process.

##### *2.1.1.1 Model of pre-existing Organizational and Personal Relationships*

This model suggests that organisations engaged in a collective resource problem voluntarily establish networks of by-product linkages. Incentives could be grounded in an economic opportunity or environmental regulation, however the most influential factor based on the model is the creation of collaborative networks building on pre-existing organizational and personal relationships (Gibbs, 2007). This is viewed as the starting point of industrial symbiosis, where the collaboration is seen as a means to achieve benefits that would not be possible when acting alone. The inter-firm interaction through personal relationships is the key to establish collaboration, and no formal organisation or coordination body is present.

There are three steps in which industrial synergies can emerge based on win-win situations. Stage one is named regional efficiency and is achieved by firms making autonomous decisions, mainly out of self-interest. Companies develop organizational relationships and take on the coordination role themselves in order to achieve higher efficiencies. Stage two is known as regional learning, where organizations engage in partnerships and increase their mutual trust, which makes the sharing of knowledge possible. Finally, the third stage is achieving sustainable development where symbiotic linkages are established and the exchange of resources start to happen (Boons & Berends, 2001, Baas & Boons, 2004).

#### *2.1.1.2 Model of pre-existing By-product Exchanges*

Another model found in literature also assumes the evolutionary approach and the absence of a third-party that coordinates development. Instead of focusing on existing personal and organisational relationships, this model focuses on the existence of symbiotic exchanges of by-products as a precondition. The model assumes the ignorance of organisations regarding the benefits, both economic and environmental, of symbiotic linkages and therefore do not acknowledge them as such. Examples from practice were often discovered by research institutions, after which companies could “springboard” and achieve novel exchanges that were economically interesting or environmentally beneficial to the region (Chertow, 2004).

#### *2.1.2 Models of Planned Industrial Symbiosis*

Another field of research, in contrast to the evolutionary approach and self-organization, focuses on planned models of Industrial Symbiosis development. This view is goal directed, resulting in the presence of a third-party responsible for coordination of the development of symbiotic exchanges. The starting point can be an industrial company operating in an industrial region or cluster, a company in search of a strategic location for efficiency or economic advantages, a public body, research institute, international development organisation or a consulting company. According to Korhonen et al. (2004), this configuration asks for active communication and collaboration and openness to new ideas.

Roberts (2004) provides a list of principles and guidelines for such coordinating bodies in order to establish new symbiotic linkages. The aim of this approach is to guide the uptake, and create win-win situations in terms of environmental quality and economic advancements in industrial regions, or in other words realization of the principles of Industrial Ecology.

**Table 2 Principles and guidelines for coordination bodies for establishing new symbiotic linkages**

	<b>Principles (Roberts, 2004)</b>
<b>1</b>	Promote opportunities to establish genuine partnerships and engagement with communities and government in developing a more responsive attitude towards sustainable practices
<b>2</b>	Locate industries strategically to optimize the material flow and capture of by – products and wastes
<b>3</b>	Co-locate industries that will benefit economically from the exchange
<b>4</b>	Capture and create possibilities to promote waste recoveries in the industrial system
<b>5</b>	Provide a catalyst to create synergies and an environment for fostering technical production in a cleaner way.
<b>6</b>	Provide an appropriate ‘Smart infrastructure’, to insure the growth of eco-industrial parks and to maintain high level of innovation as the basis of their competitive edge.
<b>7</b>	Support industry policies and incentives to encourage innovation, collaboration and commercialization of new improved product developments using materials, water and energy surplus to production and
<b>8</b>	Demonstrate commitment to the benefit of industries that have strong, sustainable development.

Related to these principles, several models have been presented in literature regarding both planned industrial symbiosis and eco-industrial parks. There are several similarities to the evolutionary models such as the notion of pre-existing linkages.

#### *2.1.2.1 Model of Coordination Bodies*

In this approach, a third-party body that is not formally linked coordinates the development of symbiotic linkages and acts as a facilitator. They are often called ‘brokers’, and range from public agencies, non-governmental organisations to private organisations. This model focuses on creating symbiotic linkages between a range of selected companies. The coordinating bodies can have both an internal focus on the industrial network, and an external focus on facilitating and influencing legislators and policy makers, financial parties such as venture capitalists or other project specific necessities (Mirata, 2004). Especially in regions or industries where coordination and communications is lacking, these coordination bodies can play an essential role (Boons & Baas, 1997).

#### *2.1.2.2 Model of Anchor Tenant*

The Anchor tenant model is quite similar to the model of a coordination body, the main difference being that in this model the coordination is concerned with a large industry and attracts several companies to engage in new transactions in the region of the industrial cluster (Lowe, 1997). Opportunities arise from outputs regarding the anchor tenant which other organisations can utilize, potentially offering economic and environmental benefits for both the anchor tenant and corresponding companies. Facilitators identify symbiotic linkages, and from the point the first ones are established more will follow, ultimately resulting in an eco-industrial park.

#### *2.1.2.3 Model of Greenfield Eco-Industrial Parks Development*

As presented in the introduction, Eco-Industrial Parks are concerned with the practical implementations of the concept of Industrial Ecology and Industrial Symbiosis. A definition of the model is given by Lowe (1997), and is concerned with consciously planning a wide range of symbiotic linkages in a particular industrial region. Authors in this field argue that new networks of Industrial Symbiosis can be uncovered and designed through research on regional resource and energy flows in an area, and linkages created with companies not yet located at the region. According to Gibbs et al. (2007), Greenfield Eco-industrial Parks should be designed phase by phase, where every individual stage should be economically possible as this ultimately contributes to the success or failure of Industrial symbiotic linkages. In this respect, this model too falls under the planned Industrial Symbiosis. Key indicators and success factors in this model are planning approaches to calendar possible revenues and subsidies, and attracting other forms of investments for infrastructure upgrading and installation (Sterr et al., 2004).

#### *2.1.2.4 Model for Brownfield Site Development*

In contrast to the Greenfield approach, the Brownfield Site Development model focuses on establishing linkages between industries currently present in the region.

This model represents a methodical search for potential connections between industries that already exist in an area. Connections are usually encouraged and facilitated with the broader view of how all the industries can become interlinked (Maltin, 2004). Other efforts focus on revitalization of urban and rural sites (Chertow, 2007). Examples of this type of planned networks are found in the UK in the regions of Humberside, West Midlands, and Mersey Banks. The Business Council for Sustainable Development-United Kingdom (BCSD-UK), in academic partnership with the International Institute for Industrial Environmental Economics (IIIEE), has coordinated and facilitated the establishment of these planned Industrial Symbiosis programs. Coordinators worked with existing industries by performing preliminary studies, hosting awareness raising workshops, collecting and analysing data, and leading in the identification and implementation of synergies at existing industrial sites (Mirata, 2004). Another example is a Brownfield project in Dallas based around a landfill site, where new facilities were mixed with existing ones to maximize their capacity and create symbiotic linkages (Chertow, 2004). In this model, as in Greenfield industrial park development, attracting new promising investors to upgrade or install the infrastructure is one of the key success factors to development, this is why public subsidies and planning concepts to estimate potential revenues are one of the key indicators (Sterr et al., 2004).

#### *2.1.3 Industrial Symbiosis, Urban Symbiosis and hybrid industries*

Japan's Eco-town program comprises many examples of such linkages tailored to regional opportunities that seem relevant to this particular research. As explained, the focus of this project is both on industrial by-products flows and possible urban markets, in this case by-product hydrogen from industry and regional mobility. Most,

if not all literature regarding IS and EIP are concerned with utilizing industrial by-product flows by other industries. However, the notion of symbiotic linkages can be extended to urban areas. Japan's Eco-town Program has aimed to integrate industrial Symbiosis and Urban Symbiosis, seeking economic and environmental benefits from geographic proximity.

A staggering 1.65 billion USD was invested in 61 innovative recycling projects (Berkel, Fujita, Hashimoto, Geng, 2009). Various commercial, municipal and industrial wastes previously discarded can now be used in industrial applications. An important motivation was the *modernisation of industry* by developing environmental businesses that utilize available technological resources at existing industries for new environmental applications (van Berkel et al., 2009). In their paper on Japan's Eco-town Program van Berkel et al. (2009) extend the Industrial Symbiosis literature with the term Urban Symbiosis, which specifically refers to the use of by-products (wastes) from cities or urban areas as inputs of industrial operations. They state that Urban Symbiosis is similar to Industrial Symbiosis as it is based on the synergetic opportunity that arises from the geographic proximity of urban waste sources and potential industrial users through the transfer of physical resources ('waste materials') for environmental and economic benefit (van Berkel et al., 2009).

As this research is rooted in both urban and industrial sectors in terms of symbiosis it impacts both the private sector and civil society. In order to categorize urban and industrial symbiosis over the various projects in the Eco-town project, two axes were formulated for the main area of benefits and the key stakeholders.

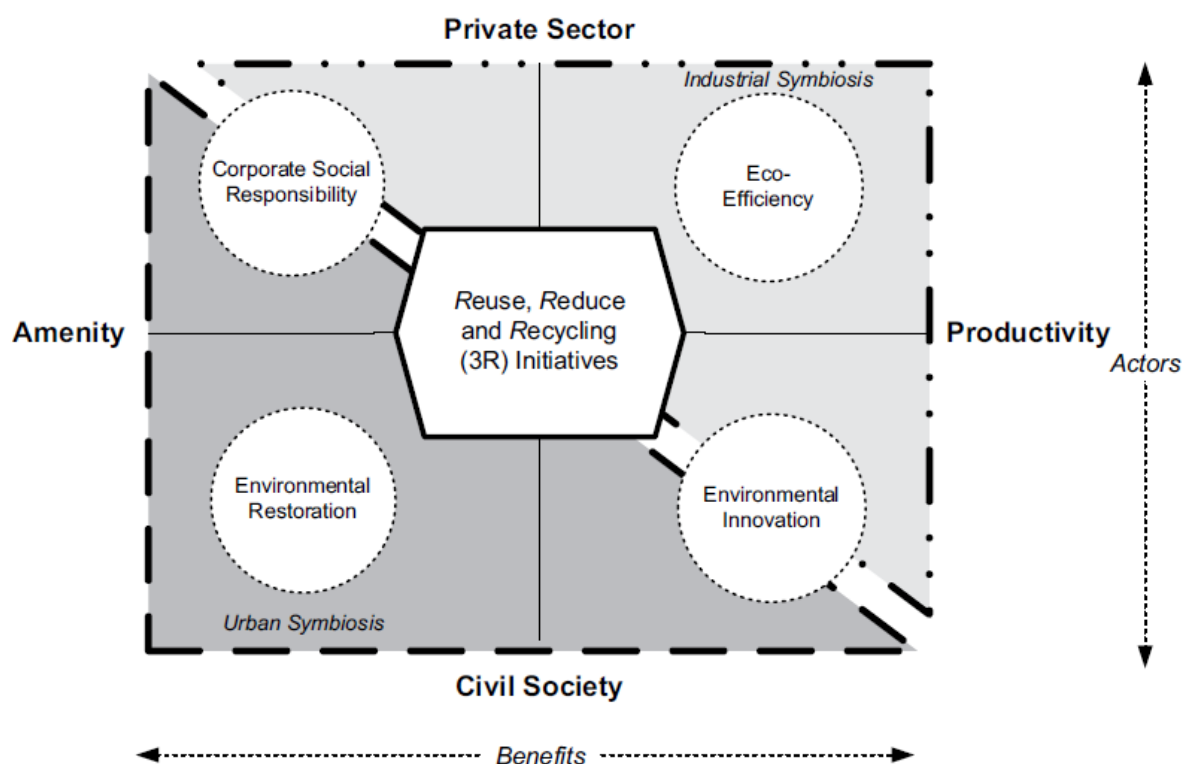


Figure 2 Characterization of Urban and Industrial Symbiosis based on impact and benefits (source: van Berkel et al., 2009)

These are shown in Figure 2, where amenity refers to the common good of citizens such as environmental quality, and productivity to the economic benefit capitalized by the private sector (van Berkel et al., 2009). Note that the private sector includes existing and emerging industries and the supply chains involved including materials, technologies and R&D (van Berkel et al., 2009).

The result is an impact diagram with four quadrants that cover the different aspects of the environmental and sustainability agendas for government, business and society at large (Berkel et al., 2009). The quadrants most applicable to this study are *eco-efficiency*: producing less waste and using less materials in productive activities (van Berkel, 2007a), and *Environmental innovation*: using environmental issues as a driver for developing new technologies, products and services (e.g. Fussler, 2004; van Berkel and Narayanaswamy, 2004). The idea of utilization by-product hydrogen is in essence on the one hand to decrease the amount of waste and on the other hand making it a useful input, which uses environmental issues such as GHG emissions in industry and mobility as a driver to develop hydrogen mobility technology and related products and services. *Environmental Restoration* is referred to as reversing environmental damage from past activities that no longer harm humans and ecosystems (van Berkel, 2009). When looking at fuel cell hydrogen mobility applications, it seems to fit more in the environmental innovation category as they attempt to disrupt current mobility technologies based on fossil fuels as a pose to reversing them. The term urban symbiosis is placed under Environmental restoration in the bottom left quadrant. When assessing the Eco-town projects placed in this category, the focus is more on reversing former environmental hazardous behaviour than where the waste stream originates (urban or industry). The example of Naoshima town seeks to adapt their existing processes to recover valuable metals from industrial wastes in order prohibit it from ending in a dump site. This corresponds well with adapting the coke oven gas stream in order to recover hydrogen.

The example of Kawasaki Eco-town is characterized as an eco-efficiency project making it an Industrial Symbiosis. As shown in Figure 3 below, the streams of industrial symbiosis and urban symbiosis are either between industries or as inputs for industries (e.g. cement and iron and steel works) from urban waste. No waste streams seem to flow from industrial processes and are utilized in urban areas. In the case of industrial by-product hydrogen, the known cases are synergies with other industry, and no cases were found where it is currently utilized in urban areas. This imposes that the current study of by-product hydrogen for mobility purposes is a novel area of research, as it combines industrial and urban symbiosis theory but views the possibility from a reversed perspective compared to the Kawasaki Eco-town example.

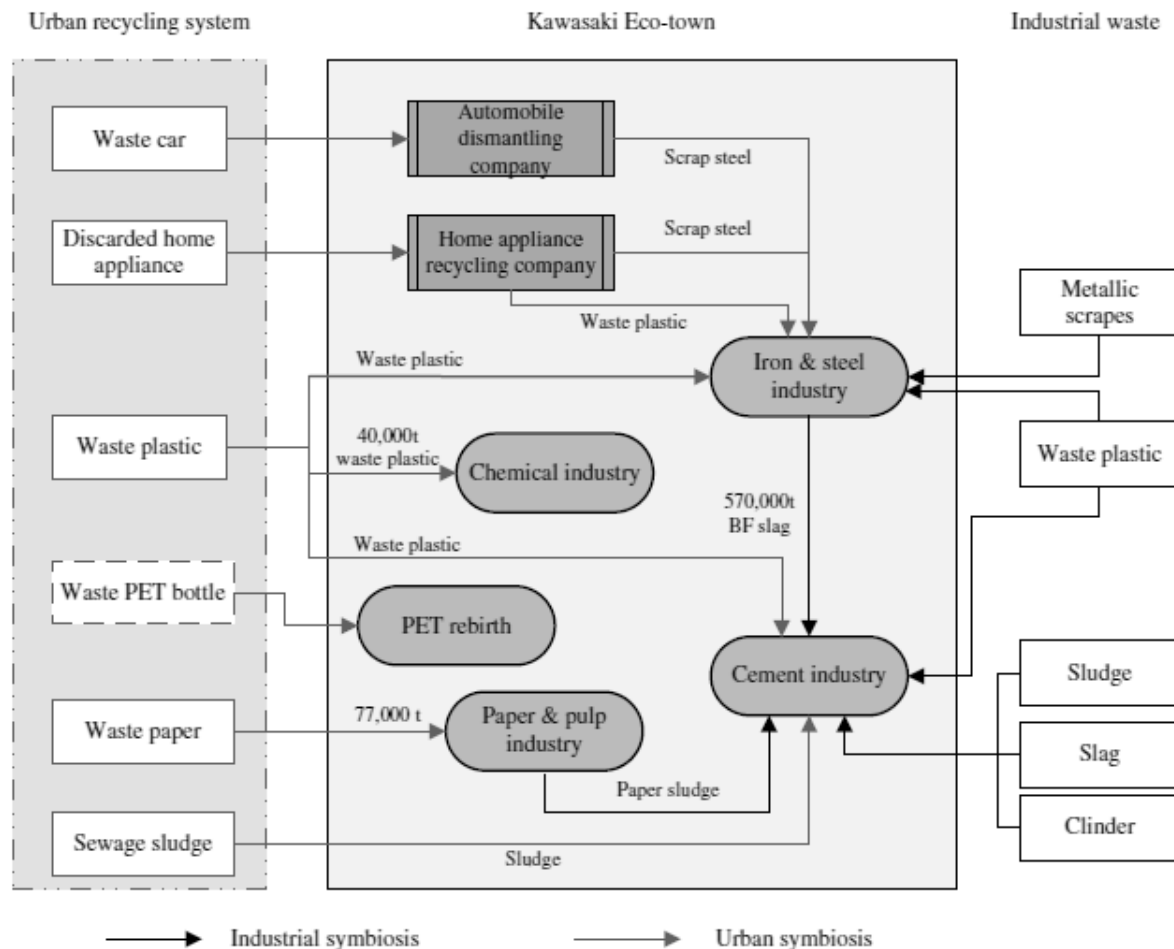


Figure 3 Material synergy network in Kawasaki Eco-town (source: van Berkel et al., 2009)

Closely related to this concept is another new concept which authors have named “hybrid industry”. Hybrid industry is an industry whose processes utilize not only fossil resources but also recycled and renewable resources as much as possible (Fujii, Fujita, Dong, Lu, Geng, 2016). Similarly, the focus is to increase the utilization of waste by industry generated by urban areas and vice versa. In transforming the current system, transitional and future systems are proposed which are shown in Figure 4 below. Note that in the transitional system, energy is regarded as a possible output from industry into urban areas, ultimately leading to an envisioned ultra-low-carbon industry.

The current prime example that fits well into the Industrial-Urban Symbiosis in a hybrid industry is transporting surplus heat from industry to urban areas. In a paper “the future of Heating: Meeting the Challenge” by the Department of Energy and Climate Change (2013) the opportunities in the UK for the recovery and re-use of industrial waste heat are assessed and range from 5TWh/yr. to 28 TWh/yr. Also, in the Netherlands the residual heat in the port of Rotterdam currently provides heating to homes in the area and possibilities to upscale this are now being explored.

Similarly, by-product hydrogen from industry for mobility purposes in the surrounding (urban) area and as symbiosis between industry and urban areas, meaning these theories can act as a system boundary.

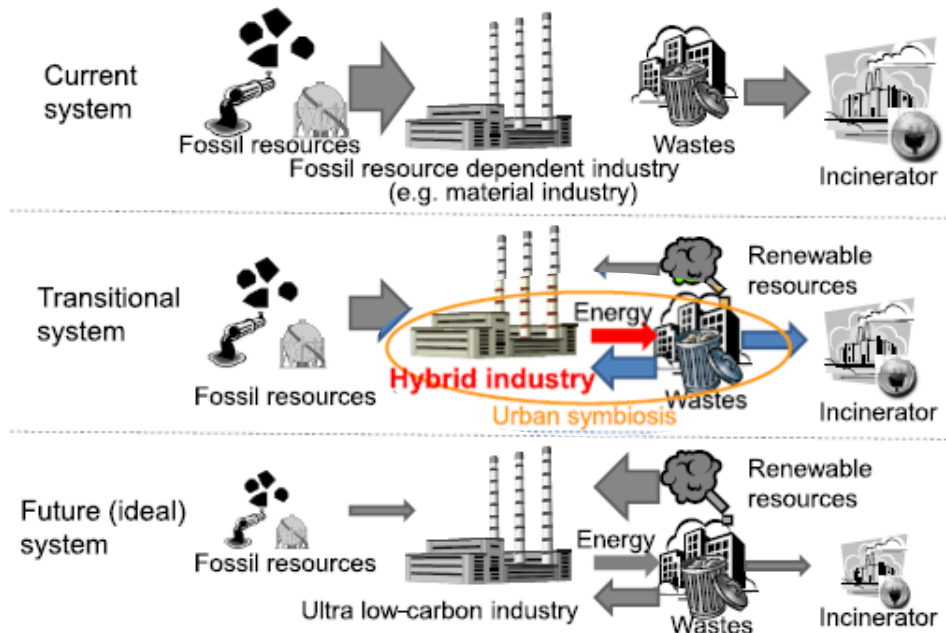


Figure 4: Features of the hybrid industry, current system and ideal future low-carbon industry (source: Fujii et al., 2016)

#### 2.1.4 Success factors for eco-innovation

A recent international survey aimed to provide insights and recommendations and boost implementation of eco-innovation. Drawing upon international experiences in a wide variety of initiatives of eco-innovation, including industrial symbiosis, urban symbiosis, eco-industrial parks and many others on a *regional scale*, the survey has provided a set of success-factors that can facilitate emergence of new initiatives. The success factors range from the need for business interests to governmental incentives. The outcomes of the survey thus strongly correlate to this study, and the findings will be used to further develop the model in extension to the general findings derived from Industrial symbiosis. Table 3 presents the success factors and descriptions as directly given in the publication by Massard, Jacquat and Zürcher (2014) as part of the eco-innova consortium - an international network of 25 partners in 20 countries all over Europe. The aim of the consortium is to support research, innovation and environmental policy makers with best practices for funding eco-innovation.

**Table 3 Success factor for eco-innovation (source: Massard, Jacquat & Zürcher, 2014)**

<b>Success factor</b>	<b>Description</b>
<b>Economic value added</b>	Direct business interests of companies in reducing expenses and/or in increasing profit by implementing synergies with other companies in the park (implementation, development, perpetuation).
<b>Policy &amp; regulation frameworks</b>	Legislation enhancing eco-innovation, sustainable development, public-private partnerships, industrial symbiosis and eco-industrial development strategies through local and regional policy action for implementation and regulatory instruments combined with innovative models.
<b>Financial incentives</b>	e.g. tax reduction and/or financial support for companies committing to sustainable practices
<b>Organizational and institutional setups</b>	Organization and setups for the operation of the park. Coordination bodies, e.g. trust companies in charge of the coordination and services for stakeholders (e.g. environmental services, risk analysis, information and training, marketing and communication, help for getting permits, “plug and play” (services) and providing a platform for cooperation among stakeholder Monitoring through independent authorities and management of common mutualized infrastructures
<b>Cooperation with Science and Technology institutions</b>	Cooperation with e.g. universities, science and technology enterprises and research centers, knowledge sharing
<b>Geographical factors and regional infrastructure</b>	Location (close to seaport, airport, highway, urban centers, historical and natural conditions), Infrastructure, size, potential for expansion
<b>Local diversity of economic activities</b>	Large opportunity to create sets of feedback flows due to the diversity of economic activities. Companies on site with activities in different sectors (e.g. wood industry, heat power generation, chemical operations and paper manufacturing
<b>Clear designation of the park as eco-innovation park</b>	Clear commitment, clear definition and differentiation from other parks (self –declaration must be reviewed) as marketing and communication standards.

## 2.2 Regional Clusters

A way of thinking about national, regional and local economies and their roles in achieving competitiveness is what authors have called clusters. Clusters have become an important mode of economic viewing and co-ordinating industries across the globe. Modern competition depends on *productivity* and *productivity growth*, and not on individual enterprises. Productivity is best described as *how* companies compete, and not on the particular fields they compete in (Porter, 2000). In his

research, Porter (1998) finds empirical evidence that local clusters have a large impact on economic development, and provide powerful benefits:

- 1) *Productivity benefits*: due to early access of better quality and lower cost specialized inputs, cheap local sourcing and minimal inventory requirements and low transaction costs. This last point is explained by a high level of trust in personal and organizational relationships. Furthermore, knowledge and information are more frequently shared due to formal or informal often face-to-face contact. Importantly, complementarities between organisations aid in ways such as joint marketing, joint-bidding and scale benefits. In short, productivity benefits arise from
  - a. *Better access to employees and suppliers*
  - b. *Access to Specialized Information*
    - i. *Personal relationships (trust)*
  - c. *Complementarities*
    - i. *Joint marketing, joint-bidding, scale benefits*
- 2) *Innovations benefits*: customer, supplier and related industry proximity leads to interaction and innovation. Also, being proximate to knowledge centres such as universities increases uptake of new designs, testing and prototypes, and qualified personnel is more easily recruited. Informal linkages and knowledge spill-overs occur more frequently in clusters, as well as localised benchmarking, all of which leads to innovation around products, processes and organizational learning.
- 3) *Formation of new businesses*: locally available information on market opportunities and potential to innovate has a positive impact on the formation of new businesses. Research shows that clusters can be an important initial market, and they reduce entry barriers. Subsequently, the knowledge and familiarity with local sources of funding (public or venture capitals) positively influence and decrease risk of new start-ups, corporate spin-off and growing businesses. Finally, specialized clusters and leading-edge business locations attract outside firms and foreign direct investors as they foresee potential benefits a cluster has to offer.

The main reason clusters work is due to the established networks between relevant stakeholders such as companies, research institutions and governing bodies, allowing for trust, knowledge spill-overs on expertise and the willingness to share assets. These networks can be formal or informal, soft or hard like a binding contract (Cooke, 2001). When looking at the various Eco-town initiatives in the previous chapter, an important driver was the creation of clusters of recycling businesses and other possible stakeholders to realize their objectives (van Berkel et al., 2009).

### 2.2.1 The Porter 'diamond'

Porter captures such a locational business environment through four interrelated influences and as presented in Figure 5 are known as the Porter diamond. A cluster is basically the manifestation of the diamond at work, and statistic evidence has proved this role of local clusters in economic development. These interrelated influences are shown as separate facets in the diamond, and named as factor conditions, in cluster firm strategy, structure and rivalry, the related and supporting (supplier) industries, and lastly the demand conditions.

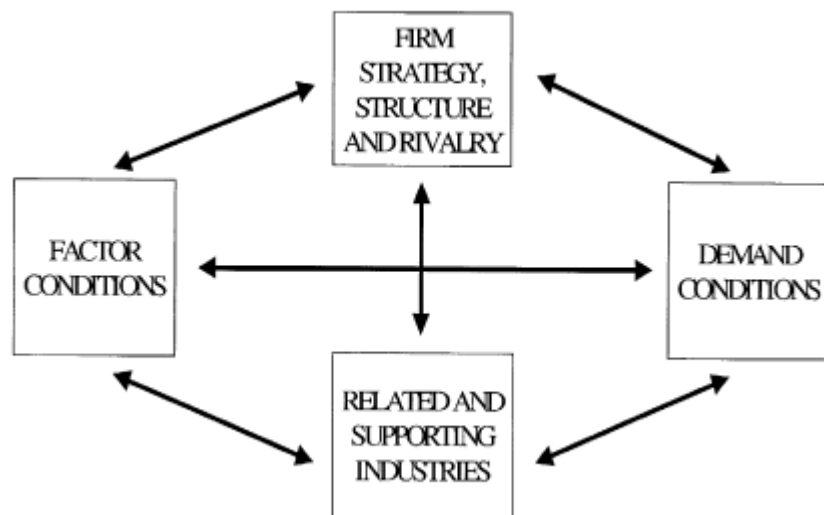


Figure 5 General framework for cluster competitiveness known as the Porter 'diamond' (source: Porter, 1998)

**Factor conditions** are described as inputs to the productive process of cluster that originate outside of the cluster, but influence the cluster competitiveness or productivity. These can be on a regional or national scale, and refer to tangible assets such as physical infrastructure in the region like roads or pipelines, but can also refer to intangible factors such as the legal system or the knowledge infrastructure.

The **Firm strategy, structure and rivalry** facet refers to the context for firm strategy and rivalry, and refers to the rules, incentives and norms governing the type and intensity of local rivalry (Porter, 1990). Local rivalry is important in order for an advanced economy to develop, in which clusters play an important role (Porter, 1990). By firms, it refers to the firms in the cluster itself, which in general means the organisations directly in the value chain for the specific product line naming the cluster. In a cluster firms can provide specialized services such as accounting or engineering, and could be in the cluster or be separate firms, while in others they are in-house departments subsidiaries (Porter, 1990). Therefore, Porter argues that the distinction between firms actually in the cluster or related firms outside the cluster can be fuzzy. The importance when analysing however is not necessarily the distinction,

but rather the inclusion of linkages and important relationships, whether they are inside or outside the cluster.

Clusters use goods and necessary services of other enterprises and organisations based in the region, which refers to the third facet – **Related and supporting industries**. For manufacturing clusters, for example, financial or construction services are a common practice.

The final facet shows the **demand conditions**, which are equally important for cluster competitiveness. Porter argues that for a cluster to be successful and sophisticated demand of local customers should be in place, and the demand should be for the specialized segments that the cluster operates in.

### 2.2.2 The GEM model

Padmore & Gibson (1998) present another model for description and assessment of strengths and weaknesses of industrial clusters. This model is especially applicable to a regional perspective on clusters, and combines the model presented by Porter while incorporating important characteristics of a regional innovation system. They argue that the regional perspective that this model allows is emerging as a better way portraying contemporary economic patterns, the basis of what is called cluster analysis (Padmore & Gibson, 1998). This model categorizes key features of clusters under three main headings: Groundings, Enterprises and Markets, which make up the name of the model.

**Groundings** refer to the supply determinants available in the region, including classical factors such as labour and raw materials, and also intangibles such as the relations of labour in the environment. All aspects are categorized under resources and infrastructure, and state that in a regional or local context shortages in some aspects compensate for abundance in others can to some extent.

By **Enterprises** they refer to the structural determinants for cluster competitiveness, which indicate the efficiency of production in a cluster. These determinants are all enterprise based, and state that an important aspect of competitiveness of a cluster a strong business community of these enterprises.

The final heading looks at **Markets**, and is used for assessing the main demand determinants of a regional cluster. Markets are not limited to the eventual customers, but both local markets that account for intermediate demand that can stem from the cluster itself and external markets to the region are important for cluster competitiveness (Padmore & Gibson, 1998).

There is no special template for a cluster, resulting in a wide variety of clusters incorporating a large range of compositions with different components. Examples of clusters include suppliers of specialized inputs like machinery and services, specialized infrastructure or necessary components to a particular field (Porter, 1998). Also, clusters often include more downstream activities and customers such

as manufacturers or companies that produce or have complementary technologies, skills or products (Porter, 1998). What often makes clusters particularly competitive is the inclusion of governmental or other institutions such as universities, standard-setting agencies, think tanks, vocational training providers, and trade organisations, which can often provide the necessary training, education, information research and technical support (Porter, 1998).

This definition captures the key elements of competitive and collaborative interaction that are characteristic for the relationships and components of clusters, and recognises the importance of proximity. Similar to literature on industrial symbiosis, clusters focus on social dimensions, and recognises key elements of competitive and collaborative interaction that characterises firm relationships (Cooke, 2001). However, in his article on cluster development using the example of biotechnology, Cooke (2001) mentions the static nature of the cluster description put forward by Porter. He argues that a key feature of clusters is that they are dynamic, and he proposes the factors shown in table 4:

**Table 4 Key features of clusters according to Cooke (2001)**

	<b>Cluster factors (Cooke, 2001)</b>
<b>1</b>	The display of a shared identity and future vision
<b>2</b>	Turbulence, as firms tend to spin-off, spin-out and start-up from other firms of institutions
<b>3</b>	An arena of dense and changing vertical input-output linkages, supply chains and horizontal inter-firm networks
<b>4</b>	A localised, third-party representative governance associations that provide the common services but also lobby government for change
<b>5</b>	It may have caused governments to develop policies to assist cluster development, especially where market failures are present
<b>6</b>	Over time, clusters can reveal features of emergence, dominance and decline

In the article, a preferred definition is proposed that incorporates the factors mentioned above as follows: a cluster is built of “geographically proximate firms in vertical and horizontal relationships, involving a localised enterprise support infrastructure with a shared developmental vision for business growth, based on competition and co-operation in a specific market field” (Cooke, 2001).

A widely cited paper by Iammarino & McCann (2006) present stylised characteristics of industrial clusters distinguished by means of the nature of firms in the cluster and the nature of their relations and transactions undertaken within these clusters. This has led to three ideal types of industrial clusters named *pure agglomeration*, *industrial complex* and *Social network*, of which characteristics are summarized in Table 5. According to Iammarino & McCann (2006) however, in reality every cluster type will contain characteristics of or a mix between the ideal types, but state that one will be dominantly present. These characteristics will help as a guideline when generating an ideal cluster for Industrial Symbiosis and by-product hydrogen.

### 2.2.3 Pure agglomeration

The main characteristic that defines a pure agglomeration is that the inter-firm relationships are not permanent, not particularly loyal and continuously changing between other firms. They do this due to changing market opportunities which leads to vigorous competition on a local scale. The cluster is characterised by open access, no free riders, and the success of such clusters is drawn merely from the presence of the organisations, and is best categorized as the 'Marshallian model of agglomeration' (Iammarino & McCann (2006)).

### 2.2.4 Industrial complex

In contrast to the pure agglomeration model, the essence of this model is characterized by more permanent, long-term relationships and frequent transactions. Examples of industrial complexes are usually related to chemicals and steel, where typically long-term investments are made regarding physical assets and buildings. An important requirement for such a cluster is proximity in order to keep the inter-firm transport transaction costs as low as possible (Iammarino & McCann, 2006). Furthermore, these required high investments lead to high entry and exit costs.

### 2.2.5 Social network

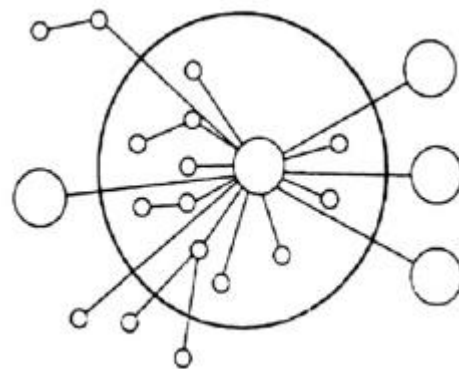
The social network model seems to be inherently related to the model of self-organised industrial symbiosis, as it argues that mutual trust relations between key decision-making actors in different organisations may be more important than the decision-making hierarchies within the individual organisations (Iammarino & McCann, 2006). One of the main differences with the other models is that geographic proximity is not necessarily a pre-condition to access the cluster. The network builds on inter-firm cooperative relations, based on a common culture and mutual trust, mainly built up from a shared history and experience of decision makers (Iammarino & McCann, 2006). However, it is argued that over the long-term, geographic proximity does tend to foster trust relations and leads to a local business environment characterised by confidence, risk-taking and cooperation. To conclude, in this model being co-located is seen as necessary on the long-term and increases the chance of access to the cluster and its benefits, however it is not seen as sufficient.

**Table 5 Three ideal style types of industrial clusters based on nature of firms, their relations and transactions undertaken (source: Iammarino & McCann, 2006)**

Characteristics	Pure agglomeration	Industrial complex	Social network
<b>Firm size</b>	Atomistic	Some firms are large	Variable
<b>Characteristics of relations</b>	Non-identifiable	Identifiable	Trust
	Fragmented	Stable and frequent trading	Loyalty
	Unstable frequent trading		Joint lobbying
			Joint ventures
			Non-opportunistic
<b>Membership</b>	Open	Closed	Partially open
<b>Access to cluster</b>	Rental payments	Internal investment	History
	Location necessary	Location necessary	Experience
			Location necessary but not sufficient
<b>Space outcomes</b>	Rent appreciation	No effects on rents	Partial rental capitalisation
<b>Example of cluster</b>	Competitive urban economy	Steel or chemicals production complex	New industrial areas
<b>Analytical approaches</b>	Models of pure agglomeration	Location-production theory	Social network theory (Granovetter)
		Input-output analysis	
<b>Notion of space</b>	Urban	Local or regional but not urban	Local or regional but not urban

### 2.2.6 Specifying the cluster – hub-and-spoke

After analysing several configurations of cluster structures, it became apparent that the potential cluster most corresponds to what has been named the “hub-and-spoke cluster. The hub-and-spoke cluster is structured around one or a few dominant firms that support the regional cluster (Markusen, 1996). According to Markusen, suppliers and other entities are spread around the hubs (or dominant firms) as if they were wheel spokes and engage in trades both internal and external to the cluster hubs and sells mainly to external customers (He & Fallah, 2011). Such clusters with one or several dominant firms which dominate the regional economy are surrounded by smaller suppliers and customers engaging in trade. In spite of being a cluster, actual cooperation and related activities among competitors within the hub-and-spoke cluster type are often lacking and the terms for cooperation are set by the hub-firms (He & Fallah, 2011).



**Figure 6 Hub-and-spoke cluster (source: Markusen, 1996)**

### 2.2.7 Cluster development

Similar to theories on Industrial Symbiosis and Eco-industrial park development, many authors have asked the question and cast their doubt on whether clusters can be built according to a grand plan or not.

Feldman, Francis & Bercovitz (2005) interpreted various case studies regarding cluster development, and found evidence that entrepreneurs are a critical element in the formation of clusters. They argue that entrepreneurs spark cluster formation and regional competitive advantage as they act collectively to shape local environments by building institutions that further the interests of their emerging industries. This concept is related to literature of complex adaptive systems, which states that systems of innovation are not a predictable linear process, but relies on the adaptive, self-organizing behaviour of entrepreneurs, who in turn rely on support of their local environment, including government resources (Feldman, Francis & Bercovitz (2005)). When entrepreneurs start companies or take advantage of new opportunities, they act as agents of change, draw on existing resources in the local environment, and eventually start to provide the environment with new resources. When examining other clusters, Feldman, Francis & Bercovitz (2005) found that this phenomenon also took place, cluster development was path dependent, with entrepreneurial activity and firm strategy playing a decisive role.

## 2.3 Institutional capacity

An important notion with the model of self-organisation and industrial clusters is the theory of institutional capacity. According to Spekkink (2012), the crucial role underlying development is based on social dimensions. In order to establish by-product exchanges, firms need to deviate from their core business which implies that the required interaction between firms is more extensive. Therefore, the ability of communities and stakeholders to deal with a collective problem or challenge is based on the amount of trust and social network. These communities can entail an institutional infrastructure with actors ranging from individual companies to governments, knowledge institutions and various interest groups that may become involved (Boons, Spekkink, and Mouzakitidis 2011).

The capacity of these actors to engage in collective action is a concept named institutional capacity, and is determined by three main dimensions (Healey et al., 2003):

- 1) **Relational capacity:** this refers to the quality of social relationships, which develops through repeated interactions with actors which results in trust and mutual recognition, contributing to stronger personal and professional relationships
- 2) **Knowledge capacity:** stronger relationships serve as a basis for the exchange and joint production of knowledge. This includes the shared conceptions of specific issues, problems and related solutions
- 3) **Mobilization capacity:** increases in relational and knowledge capacity and results in an increased capacity of actors for mobilizing joint action regarding the initiatives. An established social network around a shared strategic vision, and mobilization of resources often requires one or more actors to mobilize others.

Building and developing institutional capacity is a gradual process, and examples from earlier studies have found that this process can take many years before they result in actual symbiotic linkages (Spekkink, 2011). On the other hand, it is possible that institutional capacity has been built up through earlier interactions that were not related to the specific focus, which in industrial symbiosis literature is referred to as shared histories (Eilering & Vermeulen 2004; Heeres et al. 2004; Gibbs & Deutz 2007). Furthermore, Innes and Booher (1999) suggest that when actors have developed sufficient institutional capacity, they may be able to collaborate to influence the institutional context and public action in ways they were unable to do before.

## 2.4 Conclusion literature review

In literature, many models are presented for studying, identifying and developing by-product linkages known as industrial symbiosis. The overarching categorization of the various models refers to two fields, the notion that by-product linkages are formed on an evolutionary basis through the self-organisation of various stakeholders, and models that argue a planned approach. This last notion mostly refers to the necessity or existence of a third-party governing the development of industrial symbiosis. All models are based on empirical findings, however the debate as to which of the overarching fields is more successful for adopting symbiotic practices is ongoing. With regard to this research, some interesting findings were done especially from research in Japan's Eco-town development, where they aim to extend industrial symbiosis to using by-products for and from urban areas. Authors have proposed such practices as hybrid industries, which refers to utilization of wastes or by-products from both industrial operations to urban areas and vice versa, which in their view fits within a transitional system toward an ultimate sustainable society.

The main models regarding clusters are the Porter diamond and the GEM model by Padmore & Gibson, who both view clusters as important to local competitiveness in a globalising economy. The models are highly similar, but have slightly different categorization of important factors for cluster competitiveness, and it is argued that the GEM model has a more regional focus. There is no standard cluster form, however research has been done into categorization based on the nature of the firms inside the clusters and their transactions. This has led to three ideal style types known as pure agglomerations, industrial complexes and social networks. Furthermore, regarding the focus of this research, a cluster specification put forward by Markusen led to the concept of hub-and-spoke, where one or a few dominant firms mainly support the regional cluster.

All models regarding the development of both clusters and industrial symbiosis argue the importance of established networks, business communities and institutional infrastructure. Underlying social theory that supports this is referred to as institutional capacity, which argues that the capacity of actors engaging in collective action should be supported by established relationships (relational capacity), the joint production of

knowledge stemming from these relationships (knowledge capacity) that eventually leads to joint action (mobilization capacity).

All models have been presented and are found to be related to the focus of this research, the development of a hydrogen mobility market with by-product hydrogen. The next section offers a closer look into which models can act as inputs in order to answer the research questions stated earlier.

## Methodology & Approach

The research questions were presented in the introduction. This chapter is concerned with the methodologies and theories used to answer the separate research questions. Therefore, the questions will be stated, the process involved and the tools, method or theory that was most relevant to answer the questions. The main research question is:

***How can industrial symbiosis of by-product hydrogen from the steel industry contribute to regional hydrogen mobility by cluster development during transition to zero-emission mobility?***

This question is broadly stated as a wide scope was chosen for this research as presented in the research aim. In order to provide relevant insights for the main research question, three sub-questions were formulated.

- 1) How can relevant concepts and models of industrial symbiosis and clusters be integrated into a coherent model of requirements and indicators?*
- 2) What are the requirements specifically for by-product hydrogen and regional hydrogen mobility based on a case study of Tata Steel IJmuiden and the Province of Noord-Holland?*
- 3) What recommendations can be made in regard to the case study for the current and future situation from a systems perspective?*

These questions are summarized in table 6, along with the chapter for the results per question. The third column shows the process by the author to reach this answer, and the final column shows the corresponding background theory, method or tool used during the process. More in depth information on methodologies per sub-question are shown below the table.

**Table 6 Research questions and related chapters and methodologies**

Research question	Chapter	Process	Tool – Method - Theory
<b>Q1) How can relevant concepts be integrated?</b>	4.1	Study and combine concepts of Industrial Symbiosis and clustering literature	Desk research Porter diamond GEM model Models of Industrial Symbiosis Institutional capacity
<b>Q2) What are the requirements for by-product hydrogen and mobility?</b>	4.2	Apply and extend the developed model to the specific requirements and indicators for by-product hydrogen and hydrogen mobility	Desk Research Expert and explorative interviews Meeting attendance
<b>Q3) What recommendations can be made to the Tata Steel IJmuiden?</b>	4.3	Translate conclusions and gaps from the previous question into recommendations for Tata Steel IJmuiden.	Systems thinking approach

*1) How can relevant concepts and models of industrial symbiosis and clusters be integrated into a coherent model of requirements and indicators?*

In order to answer this question, an important first step was an extensive literature review of the various models and concepts related to industrial symbiosis and clustering. This led to a diverse set of concepts with many similarities but also wide variations. In order to develop a set of requirements and indicators for this particular topic, it is important to choose a base framework that incorporates the broad perspective. Here, the Porter diamond is found to be applicable. The four facets can supply the foundation for requirement formulation. However, during the analysis it was found that the diamond framework was often more symbolic than concrete. To aid in a complete set of requirements, the GEM model by Padmore & Gibson can be used to extend as this is concerned with a more practical analysis approach.

The next step is to uncover a set of requirements and indicators regarding models of industrial symbiosis. The overarching concepts include development based on self-organization (evolutionary) and planned by means of third party interference. As it is not possible to assess which approach or theory is most applicable at this stage, all models have to be incorporated to form requirements and indicators. As success-factors from various fields will be viewed as requirements for this research, the success-factors stemming from the international survey on eco-innovation will be incorporated as well.

The final step consists merging the findings from all fields into a coherent set of requirements and related indicators. Concerning the theories related to urban symbiosis and hybrid industries, little information was found related to what actually were the success-factors or requirements to reach this. However, as this is a new field of study with a novel approach, these fields can act as a wider scientific context in which this study can be situated. This is handled in more detail in the research scope.

*2) What are the requirements specifically for by-product hydrogen and regional hydrogen mobility based on a case study of Tata Steel IJmuiden and the Province of Noord-Holland?*

The cluster model proposed under sub-question 1 leads to general requirements and indicators for an industrial symbiosis cluster. These need to be translated to the situation of by-product hydrogen and hydrogen mobility in the region. Therefore, a case study was needed which led to the case of Tata Steel IJmuiden in the province of Noord-Holland.

Knowledge is obtained in this section by explorative interviews, attending meetings and further findings from literature in relation to the case study of Tata Steel IJmuiden and the province of Noord-Holland.

The final outcome of this question is a broad overview of minimal requirements of the current situation regarding the categories developed under question 1. Based on this and the indicators, it is possible to uncover gaps in the current situation of the case study of Tata Steel IJmuiden and Noord-Holland, which are important inputs for answering the final sub-question.

*3) What recommendations can be made in regard to the case study for the current and future situation from a systems perspective?*

Based on the findings and gaps in the previous sub-question, recommendations can be made for industrial symbiosis by clustering for Tata Steel IJmuiden. These recommendations will be formulated by the author from an interdisciplinary or systems perspective, categorized into three main elements: technology, economics and governance.

### 3.1 Research Scope

As this is such a broad analysis, a well-defined scope is vital to prevent the analysis from becoming too extensive. These are discussed in this section.

First of all, this topic is proposed to be within a certain scope based on findings in the literature review. Related to Japan's Eco-town program, the concept of hybrid industry is put forward by the author. To recap, hybrid industry processes utilize not only fossil sources, but also by-products and recycled resources within and between

urban and industry as much as possible. This was graphically displayed in Figure 4, which shows three systems: the current system, a transitional system and a future system. This research fits well in within the scope of a transitional system, since it aims to utilize by-product hydrogen as much as possible for urban and rural mobility, which can be a source until renewable hydrogen from electrolysis starts to take over. Further comments on scope include:

- 1) The analysis is concerned with the development of a regional cluster of hydrogen mobility using a by-product source from the steel industry, so the geographical boundary is the province of Noord-Holland. The hydrogen source considered is limited to the sources at the steel company, meaning other sources of hydrogen in or outside the region are excluded from the scope.
- 2) Based on the findings by Joseck, Wang & Wu (2008) on environmental impact using hydrogen from COG for hydrogen mobility in the US, this study assumes environmental and energy efficiency gains for this case study as well. Therefore, an impact study (i.e. Life cycle analysis) is excluded from this study.
- 3) Hydrogen has many applications (shown in Appendix C), but the main focus in this study is on the hydrogen mobility applications.
- 4) The findings are based on the current status (i.e. technology, regulation), and does not look into future developments. Recommendations to the company on future possibilities are however mentioned, as this can be an important factor for decision making.
- 5) In order to provide a simple market scenario, assumptions are made on possible future hydrogen demand, vehicle types and hydrogen market development in comparison to other possible drivetrains (such as battery electric vehicles). These assumptions will however be based on findings of other research papers.

## 4.1 How can the cluster concept be developed and integrated with Industrial symbiosis?

Drawing upon the findings shown in the literature study, the various concepts and indicators found in literature on clustering, Industrial symbiosis, eco-innovation parks will be combined in order to establish a complete framework and set of indicators. This seeks to answer research question 1. The starting point are the cluster concepts provided by Porter and the GEM framework by Gibson & Padmore and are used as a basis, and the framework is extended step-by-step with findings from industrial symbiosis and related concepts.

### 4.1.1 Porter diamond

As explained in the literature section. location affects competitive advantage through its influence on *productivity* and even more importantly on *productivity growth* (Porter, 2000). Importantly, how companies compete is strongly influenced by the *quality of the microeconomic business environment* (Porter, 2000). Several aspects are quite generic and economy-wide such as roads in the area or the legal system, and often more important to competitiveness in developing countries. However in developed countries the more decisive, cluster specific aspects of business environment are viewed to be important (presence of particular types of skills, suppliers or research centres).

The different facets are explained in detail in the literature section. To recap, these facets consist of:

- 1) Factor Conditions
- 2) Firm Strategy, structure and rivalry
- 3) Related and supporting industries
- 4) Demand conditions

As the exact inputs for the different facets was difficult to uncover from literature by Porter alone, extended literature was necessary. This led to the GEM model by Padmore & Gibson (1998), who in their research showed more concretely what the various facets entail.

#### 4.1.2 GEM model

Padmore & Gibson (1998) argue that the Porter diamond model of competitiveness has been more applicable to the national level, and present a model of industrial competitiveness designed for operational use at the regional level. The advantage of this model or tool is that it has been used to describe industrial clusters at various geographical scales, and assess the cluster strengths and weaknesses in a systematic way (Padmore & Gibson, 1998). The Porter diamond however is often viewed more as metaphorically, making practical implementation or usage difficult.

They refer to it as the GEM model, an acronym that in their words takes a bow toward the Porter 'diamond'. The GEM model has six determinants, which are grouped in to three overarching groups: Groundings (supply determinants), Enterprises (structural determinants) and Markets (demand determinants). Detailed descriptions of these groupings are provided in the following section. It becomes apparent that the groupings of the GEM model are closely related to Porter's diamond factors, but slightly extended. The GEM groupings and related determinants are shown in Table 7, and placed in comparison with the determinants presented by Porter. As the table shows, the Groundings constitute of the main resources in the area and infrastructure, which is the same as Porter describes as 'Factor conditions' in the region. Regarding the Enterprises, the determinants described in the GEM model are almost identical to the two facets or determinants presented by Porter. Finally, regarding the markets grouping, the GEM model divides the 'demand conditions' facet by Porter into local and external markets to the region. This division shows that the GEM model has indeed a stronger focus on regional aspects and presents a more detailed description.

**Table 7 Relations between GEM model and Porter diamond determinants**

<b>GEM grouping</b>	<b>GEM determinant</b>	<b>Porter diamond determinant</b>
<b>Groundings (supply determinants)</b>	Resources	Factor conditions
	Infrastructure	
<b>Enterprises (structural determinants)</b>	Related and supplier industries	Related and supporting industries
	Firm structures, strategies and rivalry	Firm strategy, structures and rivalry
<b>Markets (demand determinants)</b>	Local markets	Demand conditions
	Access to external markets	

The different aspects of both models are presented as potential sources of competitive advantage for a regional industrial cluster (Porter 1998; Padmore & Gibson 1998). As this research is concerned with requirements for an industrial symbiosis cluster, this section will analyse these sources of competitive advantage presented by Porter and Padmore & Gibson, and view them as requirements. The

facets by Porter and the GEM determinants will now be explained in more detail and compared, ultimately leading to an integration of the two models to present a cohesive model.

#### 4.1.3 Groundings & Factor conditions

The groundings or supply determinants are seen as the inputs to the productive process of the cluster that originate outside the cluster (Padmore & Gibson, 1998). They have been divided into the determinants of **resources** and **infrastructure**. Resources are natural, inherited or developed endowments available in the region, while infrastructure consists of physical structures and institutional arrangements to facilitate the resources (Padmore & Gibson, 1998). Included are tangible factors such as labour and raw materials, but also intangibles such as the environment labour relations (Padmore & Gibson, 1998). An important aspect here is that the ownership of specific resources or infrastructure varies from individual to private, government or the public domain. Looking at competitiveness, it is mentioned that an effective infrastructure may well compensate to some extent for resource shortages and the other way around, especially in regional context (Padmore & Gibson, 1998).

This is based on the factor conditions presented by Porter, as these also entail tangible assets such as physical infrastructure and intangibles such as the legal system, however he has not subdivided them into two groups as the GEM model does. Table 8 shows that again the Porter diamond factors are somewhat identical to the GEM indicators with slightly different terminologies.

**Table 8 Relations between GEM groundings and Porter diamond factor conditions**

GEM model indicators	Porter diamond indicators
Resource availability:	
Natural resources	Natural resources
Labour supply - skilled, flexible and reasonably priced	Human resources
Financial capital	Capital resources
Strategic geographical location	
Technology	
Infrastructure:	
Physical infrastructure (roads, ports, pipelines and communications)	Physical infrastructure
Institutional infrastructure (business association, research laboratories, training systems)	Information infrastructure
	Administrative infrastructure
	Scientific and technological infrastructure

The GEM indicators are however more extensive, adding the indicators of a strategic location and technology. The infrastructure category in the GEM model is divided into physical and institutional infrastructure. This is similar to the indicators presented by

Porter, however he has more clearly defined the different aspects of the institutional infrastructure into three categories: the information infrastructure, the administrative infrastructure and the infrastructure in the scientific and technological fields.

#### 4.1.4 Enterprises

The enterprises or structural determinants are the issues that determine the efficiency of production in the cluster, and are all enterprise-based (Padmore & Gibson, 1998). The two categories under this grounding are the firm strategy, structure and rivalry within the cluster and the related and supporting industries. As shown in the comparison, these are identical to the facets shown in the Porter diamond.

##### 4.1.4.1 Firm Strategy, Structure and Rivalry

This section refers to the context for firm strategy and rivalry, and refers to the rules, incentives and norms governing the type and intensity of local rivalry (Porter, 1990). By firms, it refers to the firms in the cluster itself, which in general means the organisations directly in the value chain for the specific product line naming the cluster. It relates to how well these firms are organized and how confident or secure, which includes measurable aspects such as the size of present firms, their birth and death rates and their financial strength, and especially the concentration (Padmore & Gibson, 1998). It also refers to competitive and growth strategies of the firms, and appropriate strategies are seen as a strong function of the stage of technological development of a particular cluster (Utterback & Suarez, 1993).

There is no one-size-fits all template for a cluster in this respect, and firms in clusters that provide specialized services such as accounting or engineering could in one cluster be separate firms, while in others they are in-house departments subsidiaries (Porter, 1990). Therefore, Porter argues that the distinction between firms actually in the cluster or are regarded as related firms not seen as part the cluster (see chapter *related and supplier firms*) can be fuzzy. The importance when analysing however is not necessarily the distinction, but rather the inclusion of linkages and important relationships, whether they are inside or outside the cluster.

Local rivalry is important in order for an advanced economy to develop, in which clusters play an important role (Porter, 1990). This rivalry is influenced by a variety of aspects of the business environment, and it is argued that the investment climate and policies towards competition set the context in this regard. Porter (1990) mentions influences such as macroeconomic and political stability, rules on intellectual property and their enforcement all contribute to the willingness of companies to invest in upgrading capital equipment, skills and technology. Therefore, the main requirements for this section are a local context that encourages appropriate forms of investment and sustained upgrading as well as vigorous competition among locally based rivals in order for a region to be competitive.

**Table 9 Comparison between GEM model and Porter diamond indicators**

GEM indicators	Porter diamond indicators
Firms strategy, structure and rivalry	A local context that encourages appropriate forms of <i>investment</i> and <i>sustained upgrading</i> <ul style="list-style-type: none"> <li>- <i>Access to Specialized Information</i></li> <li>- <i>Personal relationships (trust)</i></li> <li>- <i>Complementarities</i> <ul style="list-style-type: none"> <li>▪ <i>Joint marketing, joint-bidding, scale benefits</i></li> </ul> </li> </ul>
	Vigorous competition among <i>locally based rivals</i>

#### 4.1.4.2 Related and supplier industries

In general, clusters use goods and necessary services of other enterprises and organisations based in the region. For manufacturing clusters, for example, financial or construction services are a common practice. According to the GEM model, the success factors for such local suppliers include diversity, quality, cost and proficiency, but also important is the quality of the buyer-supplier relationships (Padmore & Gibson, 1998). Porter (1990) seconds this notion, and stresses the importance of the presence of locally based suppliers when it comes to clusters.

Another important issue mentioned in this category is the presence of competitive related industries (Porter, 1990). According to Padmore & Gibson (1998), it is argued that related industries can be an important aspect as they use similar technology, transferable human resources, similar specialized infrastructure or serve common markets. In their model, these related industries are not actually viewed as being inside the dedicated cluster, and describe the success factors as the number and quality of related firms and the existence of formal and informal linkages between them and the cluster firms (Padmore & Gibson, 1998).

**Table 10 Comparison between GEM and Porter diamond indicators for related and supporting industries**

GEM indicator	Porter diamond indicator
Local supplier diversity, quality, cost and proficiency	Presence of capable, locally based <i>suppliers</i> Presence of competitive <i>related industries</i>
Quality of buyer-supplier relationships	

#### 4.1.5 Markets & demand conditions

The final grounding of the GEM model refers to the relevant markets of the particular cluster. The demand determinants all deal with the markets for the cluster firms, which includes both final and intermediate demand which may refer to demand deviated from the cluster itself (Padmore & Gibson, 1998). The Porter diamond refers to this section as the demand conditions, where the GEM model makes a more distinctive separation between the local markets and the access to external markets.

In order for clusters to be competitive, it is important that both local market demand and accessibility to external markets is present. The presence or emergence of local markets presses firms to improve and provides insights into existing and future needs. This information is harder to gain from external markets, as local demand can also reveal segments of the market where firms can differentiate themselves, offering new opportunities. Furthermore, clusters that link different industries play an important role in giving rise to demand-side advantages (Porter, 1990). With regard to the external market, it can be important to be connected to a foreign market, centre or cluster which is further established, especially during the growth phase of a cluster (Breshnahan, Gambardella & Saxenian, 2001).

The GEM indicators for the local market demand include measurable aspects such as market size, share and growth prospects, but also standards and the quality expected by these relevant markets and the willingness of buyers to work with the local cluster. Porter (1990) merely speaks of a sophisticated and demanding local customer(s). With regard to the accessibility to external markets, the GEM model looks into the closeness, size and growth rates of these markets, but also at the characteristics of the end users and the existing market relationships. The Porter diamond refers to the importance of unusual local demand in specialized segments which can be served globally, and the customer needs that anticipate those elsewhere in the world (Porter, 1990).

**Table 11 Relations between GEM model market indicators and Porter diamond demand conditions**

<b>GEM requirement</b>	<b>GEM indicator</b>	<b>Porter diamond indicator</b>
<b>Local market demand (intermediate and final)</b>	<ul style="list-style-type: none"> <li>- Interesting market size, market share, growth prospects,</li> <li>- Standards, quality expected, willingness of buyers to work with local cluster</li> </ul>	<ul style="list-style-type: none"> <li>- Sophisticated and demanding local customer(s)</li> </ul>
<b>Accessibility to external markets</b>	<ul style="list-style-type: none"> <li>- Closeness of markets, their size and growth rates, global market share for the cluster</li> <li>- Characteristics of end users, existing market relationships, barriers to entry, trade and export barriers</li> </ul>	<ul style="list-style-type: none"> <li>- Unusual local demand in <i>specialized segments</i> that can be served globally</li> <li>- Customer needs that <i>anticipate</i> those elsewhere</li> </ul>

#### 4.1.6 Combining the model with Industrial Symbiosis and eco-innovation

The next step is to combine and categorize the various findings from Industrial Symbiosis and eco-innovation with the requirements and indicators found during the cluster research. They are categorized again under the groupings of groundings, enterprises and markets, and the findings from Industrial Symbiosis and eco-innovation are placed next to the closest corresponding cluster indicators according to findings in literature. The left column shows the requirements based on the models of clustering. Within these requirements, relevant indicators from the models shown in the literature review are placed under the requirement grouping. For distinctive purposes, the eco-innovation success factors are underlined in the tables and the indicators found in literature for industrial symbiosis are not.

Combining each grouping has led to an extensive set of requirements and indicators. During the process similarities were found between the concepts of industrial symbiosis, clusters and eco-innovation, however somewhat differently stated. During the first steps all of the indicators were placed under requirements, either distinguished or combined. These combinations are shown in table 12, 13 and 14 on the following pages.

The final model is presented in table 15. In order to create a coherent model, several requirements and indicators have been regrouped in order to decrease redundancy. The final model shows it was possible to create an overview of requirements and indicators for industrial symbiosis by cluster development, allowing for a broad assessment of the case study of by-product hydrogen and hydrogen mobility.

#### 4.1.6.1 Groundings

Factor conditions	
Combined Cluster model indicators	IS indicators
<b>Resource availability:</b>	
Natural resources	
Labour supply - skilled, flexible and reasonably priced	
Strategic geographical location	Geographic proximity between companies
	<u>Geographical factors such as close to seaport, highway, urban area, size, potential for expansion</u>
	Economic stability
Financial capital	<u>Financial incentives (taxes or subsidies for sustainable practices)</u>
Technology	
Regulation	National environmental laws and regulations
	Public-Private Partnerships
	Public policy targets (circular economy, government promotion of innovation)
<b>Infrastructure:</b>	
Physical infrastructure (roads, ports, pipelines and communications)	Cost of infrastructure
	Information management systems
Institutional infrastructure (business association, research laboratories, training systems)	(Industrial Symbiosis) Research programs (e.g. circular economy)
	Nature of interaction among industry, policy makers, and regulators
	<u>Cooperation with Science and Technology institutions</u>
	Institutional capacity
Regional infrastructure	<u>Regional infrastructure</u>
	<u>Local/regional policy action for implementation</u>
	<u>Regulatory instruments</u>

Table 12 Combination of cluster and industrial symbiosis indicators for Groundings

#### 4.1.6.2 Enterprises

Related and supplier industries	
Cluster indicators	IS indicators
Presence of capable, locally based <i>suppliers</i> based on diversity, cost, quality and proficiency	Costs of virgin inputs, economic value of waste and by-products
	Physical and chemical attributes of in- and output streams
	Local availability of decision-making power
	embeddedness in business and public networks
	<u>Economic value added</u>
	<u>Local diversity of economic activities</u>
Presence of competitive related industries	
Quality of buyer-supplier relationships	Openness to each other and to new ideas
	Awareness
	Level of social interaction and mental proximity
	Risk perception
	Trust
	Open communication

Table 13 Combination of cluster and industrial symbiosis indicators for Related and supplier industries

Firm strategy, structure and rivalry	
Combined cluster indicators	IS indicators
Cluster firm strategies <ul style="list-style-type: none"> <li>○ Access to Specialized Information <ul style="list-style-type: none"> <li>▪ Personal relationships (trust)</li> </ul> </li> <li>○ Complementarities <ul style="list-style-type: none"> <li>▪ Joint marketing, joint-bidding, scale benefits</li> </ul> </li> </ul>	<u>Clear designation of the park as eco-innovation park</u>
	Marketing
	Detailed and flexible planning for medium and long-term goals
	(Environmental) Information disclosure
	Trainings and educational programs
	Demonstrated company management leadership
Firm rivalry - vigorous competition among <i>locally based rivals</i>	
Firm structure - a local context that encourages appropriate forms of <i>investment</i> and <i>sustained upgrading</i>	<u>Management of mutualized infrastructures</u>
	<u>Coordination bodies</u>
	<u>Platform for cooperation</u>
	Cooperation with external partners

Table 14 Combination of cluster and industrial symbiosis indicators for Firm strategy, structure and rivalry

#### 4.1.6.3 Markets

GEM indicator	Porter diamond indicator
<i>Local market demand (intermediate and final)</i>	
Interesting market size, market share, growth prospects, standards, quality expected, willingness of buyers to work with local cluster	Sophisticated and demanding local customer(s)
<i>Accessibility to external markets</i>	
Closeness of markets, their size and growth rates, global market share for the cluster. Characteristics of end users, existing market relationships, barriers to entry, trade and export barriers	Unusual local demand in <i>specialized segments</i> that can be served globally Customer needs that <i>anticipate</i> those elsewhere

**Table 15 Combination of cluster and industrial symbiosis indicators for Markets**

#### 4.1.6.4 Cluster for Industrial Symbiosis Model

### Groundings

<b>Factor Condition requirements</b>	<b>Indicators</b>
Resource availability	Natural resources
	Labour supply – skilled, flexible and reasonably priced
	Strategic geographical location
	Financial incentives
	Available technology
	Costs of virgin inputs, economic value added of waste and by-products
	Physical and chemical attributes of in- and output streams
Infrastructure	Physical infrastructure
	Institutional capacity
	Regional infrastructure
Regulation	Public policy targets
	Environmental laws and regulations
Ownership	

### Enterprises

<b>Related and supplier industries requirements</b>	<b>Indicators</b>
Presence of capable, locally based suppliers and related industries	Local diversity of economic activities
Qualitative buyer-supplier relationships	Awareness
	Level of social interaction and mental proximity
	Open communication
	horizontal inter-firm networks
	Openness to each other and to new ideas
<b>Firm strategy, structure and rivalry requirements</b>	<b>Indicators</b>
Cluster firm strategies	Clear designation of the eco-innovation cluster
	Complementarities: <ul style="list-style-type: none"> <li>- Access to employees and suppliers</li> <li>- Access to specialized information</li> <li>- Joint bidding and marketing</li> </ul>
	Detailed and flexible planning for medium and long-term goals
	Environmental information disclosure
	Training and educational programs
	Demonstrated company management leadership
	Management of mutualized infrastructures
	Coordination bodies
	Platform for cooperation
Cluster firm structure	Cooperation with external partners
	Dense and changing vertical input-output linkages

<b>Markets</b>	
Sophisticated and demanding local market	Market size and growth prospects
	Standards
	Quality expected
	Willingness to work with cluster
	Customer needs that <i>anticipate</i> those elsewhere
Accessibility to external markets	Global market share for the cluster
	Customer needs that <i>anticipate</i> those elsewhere

**Table 16 Final Cluster model for Industrial Symbiosis**

## 4.2 Model application to case study

In order to provide insights on the requirements for the case of by-product hydrogen for mobility, the developed framework will now be applied to the case study of Tata Steel IJmuiden and the province of Noord-Holland. Each grouping is treated separately in order to provide an overview of how the model translates this specific case study. This is done according to the broad scope of this research, and in order to provide an assessment that is as complete as possible within the timeframe, this section strives to look into all requirements incorporated in the model. However, during the course of research it became evident that several gaps in the case study exist with regard to the model. These gaps will be further described in the result section hereafter. Both literature and explorative interviews were used in a heuristic approach to provide the following overview.

The model presented in the previous chapter follows the structure of groundings, enterprises and markets. However, for readability purposes this structure is altered in this section. In order to provide context on what hydrogen mobility actually entails, the markets section will be handled first. First an overview is provided on relevant hydrogen fuel cell applications. Then an overview of international development is presented, starting with a wide scope of global and European markets and gradually narrowing down to the regional scope of Noord-Holland. This provides a funnel in which the initial context on hydrogen mobility is provided and ends with what the implications and requirements are for Noord-Holland and specifically for Tata Steel IJmuiden.

### 4.2.1 Markets – Demand conditions

#### 4.2.1.1 Hydrogen mobility market applications

In general, there are two types of drivetrains for powering vehicles with hydrogen – an Internal Combustion Engine (ICE) and a Fuel Cell in combination with an Electro motor known as a Fuel Cell Electric Vehicle (FCEV). The maximum efficiency of a FCEV is approximately 70%, which is almost double that of a hydrogen ICE (40%). Currently the fuel cell stacks are decreasing in market price, making it possible for them to drive hydrogen ICE out of the market and which is why hydrogen mobility is mainly focusing on this technology (FuelCellToday, 2013). Furthermore, a fuel cell has no moving parts in contrast to an ICE, resulting in a decreased risk of engine failure, increase in reliability and lower maintenance (Roeterdink et al., 2010).

Already today there are FCEVs operational, of which approximately 25 in the Netherlands (Interview Jaap Oldenziel, 2016). The majority of large car manufacturers currently have prototypes or close-to-production models with hydrogen drivetrains in their portfolio. The Hyundai ix35 is currently commercially available, and Toyota has also introduced their Mirai model, of which two are currently owned by the Dutch Government. The Fuel Cell technology is also appropriate for taxi's and delivery vans, especially because they operate centrally and over long distances. However, these applications are currently not produced into

suitable vehicles. For this reason, recently at Schiphol airport (province of Noord-Holland), taxi concessions were granted to businesses to operate 168 Tesla Model S battery electric vehicles (BEVs) due to more stringent zero-emission concession demands, showing that BEVs are currently further in development and are the preferred choice (Interview Ed Koelemeijer, 2016).

Hydrogen fuel cell buses are also already operational in several parts of the world, and even in Amsterdam the GVB operated a pilot of 2 hydrogen buses until recently. A report by McKinsey and Company (2012) states that in order to realize regional zero-emission bus transportation, for distances up to 600 km a day with average speeds, FCE buses are the only option, and in urban areas BE buses are also possible. In order to make FCE buses competitive with BE buses, support from policy and a price drop is needed in the Total Cost of Ownership (TCO) (Roland Berger, 2014). Current innovations regarding zero-emission buses are needed, and studies have shown that urban buses have an average speed of 17 km/h in cities, making them ideal candidates of electric drivetrains. However, only electric using battery packs will result in a relatively low range, so the idea is that urban buses are equipped with a large battery pack and extended with a small fuel cell that continuously produces electricity. This way they fill up the battery while the battery essentially does the work. Rural buses are to be equipped with a larger fuel cell and smaller battery, which is currently being investigated (Interview Jaap Oldenziel, 2016).

In the heavy duty vehicle range for freight transportation, it was found that they often operate at relatively low speeds similar to urban buses in areas such as the Rotterdam harbour and its terminals. In these cases, the focus is also on small fuel cells providing electricity to a larger battery (Interview Jaap Oldenziel, 2016). Under this category potential street sweeping machines and garbage trucks may also be placed. So for heavy duty vehicles suitability is highest in regional transport, because in the case of international transport the hydrogen storage becomes too voluminous and will require extremely large storage capacities (Green Car Congress; HyTruck, 2014).

Forklifts and other specialty vehicles also present potential markets. In fact, forklifts already present a positive business case with a positive allowable hydrogen price, and currently in the US 5400 FC forklifts are operational in warehouses (Landing, 2014a). Other options include luggage and cargo towing tractors, passenger transportation and aircraft fuelling at airports known as Ground Support Equipment (GSE). These applications are said to be interesting because of their large volumes, long operating times and central operations (Interview Ed Koelemeijer, 2016). Finally, although not mobile themselves, Ground Power units are an interesting option, and is a relatively pure-purpose application not in need of expensive ancillary equipment (Ballard Power Inc., 2012). Currently, these applications run on diesel, which causes a lot of emissions around working staff and leads to complaints (Interview Ed Koelemeijer, 2016).

#### 4.2.1.2 External markets to the province of Noord-Holland

Realising deployment of a hydrogen and fuel cell market in the Netherlands and the province of Noord-Holland is only possible when the market takes off on a European scale. One of the reasons for this is the relatively small auto industry present in the Netherlands, meaning the market providers produce their products for a range of countries. Furthermore, an important advantage of hydrogen mobility is the action radius, which is why it is essential for various mobility applications and infrastructure to be able to be connected to external hydrogen infrastructures. This section provides an overview of initiatives of external market formation that can be of influence. Further included are several national and international partnerships or consortia that have been formed in order to realize these market developments.

##### 4.2.1.2a Global hydrogen mobility development

This section provides an overview of the most important developments regarding hydrogen mobility in and outside of Europe.

#### Fuel Cell and Hydrogen Joint Undertaking, European Union



Starting 2003, the European Commission has sought to bring together key stakeholders with regard to hydrogen mobility by establishing the European Hydrogen and Fuel cell technology Platform (HFP). The ultimate goal was to create a vision towards a hydrogen-orientated energy system by 2050 and the corresponding developments needed by 2020. By 2008, this initiative had developed into the first Industrial initiative under the European Union Sustainable Technology Plan (SET) which was named the 'Fuel Cell and Hydrogen Joint Undertaking (FCH JU). It is referred to as a *public-private partnership* between the European Commission, a community of research organisations, and hydrogen and fuel cell industry. The main focus is to accelerate and coordinate the development and deployment of fuel cell and hydrogen technologies. The project falls under the EU Horizon 2020 Framework Program, where the initial phase had a budget of €1.33 billion, and the second phase (FCH 2 JU) will continue until December 2024. The main goal is to achieve a European platform that is reliable to which industry, research and local, national and European officials are committed. The structure is industry-led, meaning the proposed research programs match the expectations and needs of industry.

More concretely, the FCH 2 JU aims to improve the performance and reduce the cost of products and demonstrate the large-scale readiness of technologies to enter the market in the fields of energy (the production and distribution of hydrogen, storage and stationary power generation) and transport (buses, cars and refuelling stations). The project further aims to implement a series of hydrogen refuelling stations between 2014-2020 in order to aid in the establishment of an initial network and the R&D requirements. The first step of the FCH 2 JU program has awarded a project for deploying 110 FCEVs that will be serviced by twelve new and six existing hydrogen refuelling stations. Subsequently, these series of initial roll-outs are expected to be

embedded in wider national (EU Member State level) or regional development initiatives known as “H2 Mobility” initiatives.

### European trans-national Transport Network Program (TEN-T)

One of Europe’s key frameworks is the trans-national Transport Network Program (TEN-T), which aims to use large available budgets (multi-billions) for funding projects around the strengthening of Europe’s key infrastructures. The first of several projects was the Hydrogen Infrastructure for Transport (HIT) project, where Denmark, France, Sweden and the Netherlands joined forces to develop deployment scenarios for a hydrogen network. As part of this project, one refuelling station was realised in the Netherlands and two in Denmark, and a second HIT project is currently being developed (Van Hoof, Van der Meer, Van der Woude, 2015). HIT-2 is aimed at the next crucial steps for hydrogen network expansion, and consists of several country partners: The Netherlands, Poland, Belgium, Finland, Sweden and the city of Riga. The project has three main activities consisting of national implementation studies and plans, infrastructure realisation/HRS deployment and strategic corridor analysis and plans. Figure 7 shows the aim of the development of a HRS infrastructure along so called ‘key TEN-T corridors’ in order to establish a basic infrastructure, which are displayed in the different colours. These corridors are viewed as the main Europe wide connections.



Figure 7 Main European corridors for infrastructure network coverage (source: Van Hoof, Van der Meer, Van der Woude, 2015)

For a basic European coverage, refuelling stations need to be present along these corridors. Figure 8 shows the existing and planned hydrogen refuelling stations according to TEN-T. When comparing to the existing (green) and planned (orange) hydrogen refuelling station locations, it can be concluded that there are many steps to take to establish a basic European wide coverage. Interestingly, the HIT-2 research mentioned above states that hydrogen refuelling station networks could evolve further following a cluster approach based on local refuelling station development in major cities. This underlines the need for clustering as presented in this study.

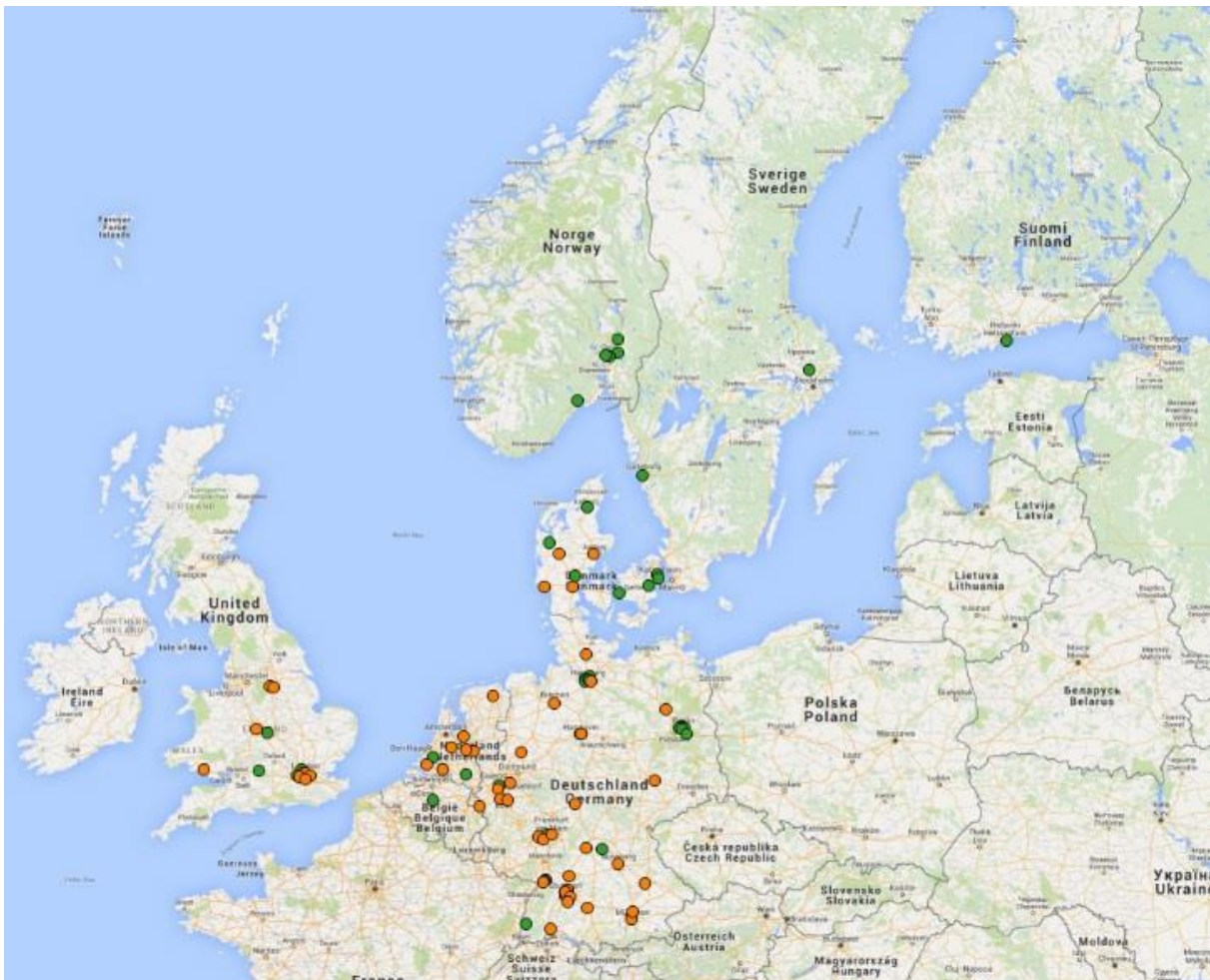


Figure 8 Current and planned hydrogen refuelling stations according to TEN-T (source: (Van Hoof, Van der Meer, Van der Woude, 2015))

### Clean Energy Partnership (CEP), Germany

Led and managed by the Ministry of Transport and Infrastructure, The CEP is a joint initiative of government and industry aiming to test hydrogen as fuel, their applications and refuelling. It is part of the National Hydrogen and Fuel Cell Technology Innovation Programme (NIP) since 2008, and consists of 20 members including car companies, utility companies, public transport providers, hydrogen

infrastructure companies and refuelling station operators. The programme will end in 2016, resulting in a market preparation of 100 vehicles that are privately owned, fuel cell buses on regular urban routes and HRS network expansion to approximately 50 HRSs along the main motorways and in metropolitan regions. Total investments by the companies and government are over €40 million.

## **H2 Mobility, Germany**

Various industry partners came together in 2009 to develop scenarios for the build-up of a hydrogen infrastructure. Based on the developed roadmap, a core group of six members (Air Liquide, Daimler, Linde, OMV, Shell and Total) started to invest in the expansion of the 50 HRSs by the CEP to 400 HRSs in 2023. Based on their scenarios, the consortium expects that a total investment of approximately €350 million will be needed to establish the necessary infrastructure. The partnership is subject to evolution, and adding to the core group partners from the automotive industry (Toyota, Honda, Hyundai, Volkswagen, BMW and Nissan) along with NOW (as interface to Germany's federal government) and have joined as part of the second phase of the project. As of this phase the project can now be categorized as a joint-venture who pursues the remaining HRS infrastructure.

## **UK H2 Mobility, United Kingdom**

In the United Kingdom, a large group of industrial companies in the business of fuel cell technology, energy utility, industrial gas, fuel retail together with global automotive manufacturing companies and the FCH JU and UK governments have started a collaborative project for hydrogen mobility. The start of development was in 2015, and aims for an initial network of 65 HRSs and financing of 62 million pounds before 2020. As a first step in 2014, funding was announced for the initial build-up of 15 HRSs by the end of 2015, accounting for a total of 11 million pounds, of which approximately one third was contributed by industry and the rest by the UK Government.

## **H2 Mobility France**

Following in the footsteps of H2 Mobility of Germany and the United Kingdom, the French formed the French Association for Hydrogen and Fuel Cells, bringing together private and public stakeholders on various levels. The initiative is supported by the Ministry of Ecology, Sustainable Development and Energy, and aims for a coordinated transition. The initial partnership is co-funded by 25 organizations together with the EU TEN-T HIT project. The French initiative differs from the H2 Mobility Germany, as the first focus is large captive fleets equipped with fuel-cell range-extendors that require 350 bar for guaranteed utilization, where Germany focuses on a 700-bar network for passenger cars in the private market. This way, they hope to mediate the risks of initial underutilization, and requires lower investments for HRS installation.

## Asia and the United States

Alongside Europe, Asia and the United States have initiated several deployment projects for hydrogen mobility. In Asia, Japan and South Korea have taken a leading role, where Japan has initiated a private-sector partnership known as the Fuel Cell commercialization Conference of Japan (FCCJ) as early as 2001. With its 108 members, 27 companies make up the board members, 42 companies are general members, and the rest are either associate members or advisory members. The aim was to operate 100 HRSs before 2015, meaning they can be viewed as true pioneers in the hydrogen mobility industry.

In the US, hydrogen mobility is mainly based in California, where in 1999 six private-sector companies joined forces with two California state Government agencies to form the California Fuel Cell Partnership. The current near term outlook for a network of HRSs consist of over 50 refuelling stations.

### 4.2.1.2b Hydrogen mobility in the Netherlands

The following table 17 shows the current and aimed Hydrogen refuelling stations for the Netherlands during the market preparation phase. These findings are based on research done by the National Hydrogen Platform and were presented during a general assembly by the Task Group for hydrogen and infrastructure & mobility market development (presentation Fred Hagendoorn at NWP, 29-09-2016).

**Table 17 Active and planned hydrogen refuelling stations in the Netherlands according to National Hydrogen Platform (source: presentation Fred Hagendoorn, 2016)**

Location	Status	Planned opening
<b>Rhoon Rotterdam</b>	Active	Operational since sept. 2014
<b>Helmond</b>	Active	Operational since 2013
<b>Breda</b>	Business case phase	End of 2017
<b>Den Haag Binckhorstlaan</b>	Planned	Beginning 2017
<b>Arnhem</b>	Planned	
<i>Aimed infrastructure expansion for LDVs</i>		
<b>Rotterdam Noord</b>		Preferably 2018-2020
<b>Amsterdam Schiphol</b>		Preferably 2018-2020
<b>Amsterdam A1</b>		
<b>Utrecht</b>		Preferably 2018-2020
<b>Apeldoorn/Deventer</b>		Preferably 2018-2020
<b>Eindhoven</b>		Preferably 2018-2020
<b>Venlo</b>		Preferably 2018-2020
<b>Twente</b>	Research phase	
<b>Zwolle/Pesse</b>	Research phase	
<b>Groningen/Delfzijl 1 of 2 locations</b>		
<b>Maastricht</b>		
<b>Tiel/Geldermalsen</b>	Research phase	Preferably 2018-2020
<i>Recent expressed interest</i>		
<b>Heerhugowaard</b>		
<b>Leeuwarden</b>		
<b>Pending Oude Tonge</b>		

As shown in table 17, two hydrogen refuelling stations are currently active for several years in the cities of Rhoon and Helmond (both outside Noord-Holland). The table further distinguishes between actually planned and aimed expansion, where the latter merely reflects the desired locations for expansion according to findings by the National Hydrogen Platform. Currently, there are several hydrogen pilots being established in regions in the Netherlands. These pilots are mainly to gather knowledge and measure the total cost of ownership related to hydrogen mobility, particularly related to hydrogen buses. Furthermore, the aim is to stimulate a hydrogen economy, reach climate goals and drive on the automotive industry. The pilots were established with a subsidy of 850 thousand euros from the Ministry of Infrastructure and Environment, alongside private investments and regional governments. In total, 5 pilots for hydrogen buses are established in the Netherlands:

In the province of **Zuid-Holland** or more specifically the Hoekse Waard Goeree Overflakkee, a pilot of 4 hydrogen buses is currently being established. Cooperative parties include the province of Zuid-Holland (funding and public transport client), Connexxion (transport company), FCH-JU (funding) and the Ministry of Infrastructure and Environment (funding). The project is part of the European 3Emotion project which falls under the FCH-JU, and the concession of the Hoekse Waard Goeree Overflakkee area. The used infrastructure will be an existing HRS in Oude Tonge, which has been established by the Greenpoint Consortium made up of Siemens, linde Gas, Eneco/Stedin and the Van Peperstraten Group.

Currently **Rhoon** holds one of the few existing hydrogen refuelling stations owned by Air Liquide. For the bus pilot in Rotterdam a cooperation between RET (transport company), FCH-JU (funding) and the ministry of Infrastructure and Environment (funding) was established, and has a scope of 2 hydrogen buses. Similarly to Zuid-Holland, the project falls under the 3Emotion project of the FCH-JU, and the idea is to make use of the existing HRS in Rhoon.

A pilot in **Eindhoven/Helmond** aims to convert existing diesel buses into hydrogen buses (Phileas), for which a consortium was founded. It consists of the province of Noord-Brabant (funding and public transport client), Connexxion (public transport company) and the Ministry of Infrastructure and Environment (funding). Furthermore, a foundation named 'stichting zero emissie busvervoer' has an advising role, WaterstofNet (hydrogen infrastructure), VDL (original equipment manufacturer of the buses) and the municipality of Eindhoven (funding) contribute to the consortium. The plan is to expand the existing hydrogen infrastructure in Helmond, where currently a HRS is operational (not commercially).

In **Groningen** plans exist to start a pilot with 2 hydrogen buses, for which chemical company AkzoNobel will be the supplier of certified green (by-product) hydrogen. A HRS will be built in chemical park Delfzijl, and apart from AkzoNobel the consortium consists of the Province of Groningen (regulation), public transport bureau Groningen-Drenthe (public transport client), Qbuzz (public transport company), CNG-

Net (will provide the infrastructure) and the Ministry of Infrastructure and Environment (funding).

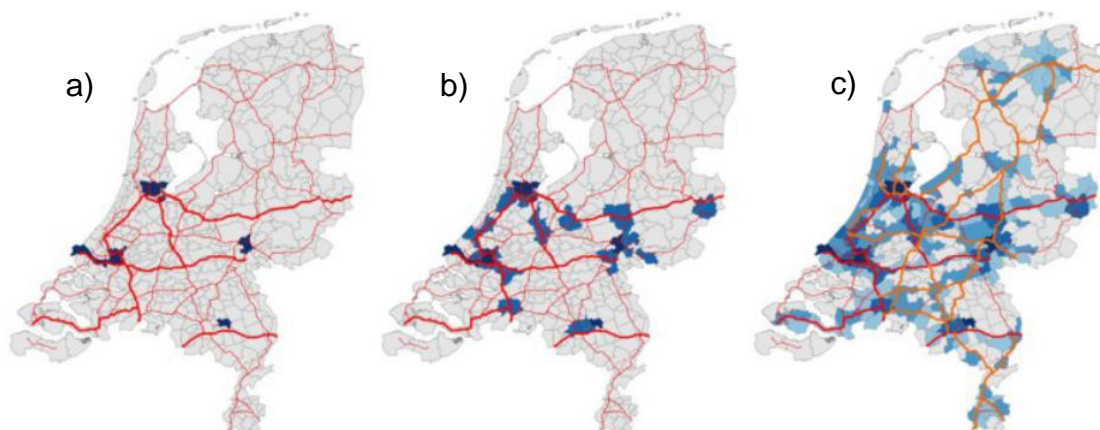
**Gelderland** is working on a business case for two hydrogen buses. The consortium consists of the Ministry of Infrastructure and Environment (funding), the province (is the client), TenT (funding). CNG-Net will take care of the infrastructure and Connexxion acts as the public transport company.

#### *4.2.1.3 Market Growth prospect for the Netherlands*

In 2013 the Ministry of Economic Affairs of the Netherlands presented the 'Energy Agreement for sustainable Growth', aiming at an energy transition towards 2050. (Werkprogramma NWP). For the sector mobility and transport, the agreement states that to the end of 2035 all newly sold personal vehicles should be capable of driving zero-emission. Hydrogen receives special attention, as the European Commission has requested an action plan for hydrogen infrastructure and market development before 2020 (Ministry of Infrastructure and Environment, 2014). The action agenda states that by this time 20 HRSs should be installed, 2.000 FCEVs, 100 buses and 500 delivery vans should be deployed (SER, 2014).

The ultimate goal is zero-emission mobility in 2050, where the share of hydrogen vehicles in the entire vehicle park is assumed to become approximately 40% (SER, 2014). This percentage is based upon the assumption that battery electric mobility will gain a significant market share, and should technology in this field fail to improve, the hydrogen mobility share could be even greater (SER, 2014). This is because the possible applications for hydrogen mobility are said to be much broader. This assumption is underlined by an approved study by the Directorate-General for Mobility and Transport of the European Commission. Based on several scenarios and model projections, with substantial learning rates of approximately 6% and steep decreases in costs, fuel cells can indeed achieve large market shares reaching over 38% (Exergia, Ecorys, ICCS/NTUA, AUTH., 2011).

With regard to the action plan before 2020, this report takes a less optimistic view. This because this document also states expected growth numbers regarding fuel cell vehicles and refuelling stations as of 2014 which currently do not reflect reality. The market growth prospect for the Netherlands is shown in three market development phases in Figure 9, the phases before mass market growth (ECN, 2015). The highlighted red highways shown are part of the main corridors according to the European trans-national Transport Network Program (TEN-T) shown in Figure 7. Along these corridors are the favourable initial markets, which is why the first signs of market development are expected to be here. The orange highways are indications of additional networks after the main corridors have been established. The blue areas indicate coverage for hydrogen mobility due to established hydrogen refuelling stations.



**Figure 9 Market development of hydrogen infrastructure (ECN, 2015)**

The different market stages are shown in Table 18. The indication of the fleet size and amount of hydrogen refuelling stations is adapted from the scenario presented by SER (2014) and the hydrogen uptake numbers mentioned above, and the total fleet size of the Netherlands (CBS, 2016). It does not take into account the growth projections of the entire fleet as this is highly insecure given the many technological developments in the mobility sector such as self-driving cars. Further detail on the fleet types is presented in the next chapter on approximation for the demand in Noord-Holland.

**Table 18 Projected market scenario phases developed by the author**

Market development phase	Indication of fleet size NL	Indication amount of hydrogen refuelling stations NL
<b>a) Market preparation</b> 2016 - 2020	<100	5-20
<b>b) Early market introduction</b> 2020 - 2025	500-5000	20-50
<b>c) Market commercialisation</b> 2025-2035	100.000-200.000	50-200
<b>d) Mass market</b> >2035	40% market share – 5.000.000	1000-1500 (4000 stations total, 40%)

#### 4.2.1.4 Approximation for Noord-Holland demand

The entire road transport market in Noord-Holland constitutes of approximately 1.5 million road vehicles (CBS, 2014). According to the models mentioned previously, this constitutes of a hydrogen mobility market share of approximately 600.000 vehicles. For purposes of reaching a general indication of the potential market size, a distinction is made between a low duty vehicle (LDVs) and heavy duty vehicle (HDVs) as these vary greatly in their fuel consumption. When assessing statistics on actual numbers of LDVs and HDVs, several road transportation vehicles such as specialty vehicles were excluded from analysis as these are not yet available, so no

number for hydrogen usage by these vehicles was found. Therefore, the market approximation shown below is lower than the 600.000 shown above. Note that the following approximation is merely to provide an overview of possible demand prospects and may differ greatly from reality. A more in depth research into actual efficiencies and specific numbers of different types of vehicles is necessary for a more detailed description.

#### *Light duty vehicles*

Most car manufacturers have tested and demonstrated FCEVs and are developing commercial vehicles for market introduction. Hyundai is seen as a front runner and has produced over 300 vehicles, and companies such as Toyota, Honda, BMW and Mercedes have followed. Currently, there are roughly 25 FCEVs operational in the Netherlands, which is less than was expected (Interview Jaap Oldenziel, 2016). However, the manufacturers agree that FC technology will play an important role if not dominate the automotive industry in 30 to 50 years (FuelCellToday, 2013).

LDVs in this regard comprise of personal vehicles and delivery vans (private and company owned). These can be taxis, rental cars, personally owned vehicles and delivery vans for people transportation. Altogether, the amount of LDVs in the province of Noord-Holland is approximately 1.3 million (of which potentially 500,000 expected FCEVs) which combined drive an average of approximately 13,500 km (CBS, 2016). As personal vehicles are currently commercially ready, quite an accurate assumption can be made for the hydrogen fuel consumption, which is approximately 1kg/100km.

#### *Heavy duty vehicles*

Heavy duty vehicles (HDVs) are viewed as company owned vehicles, namely trucks, tractors, buses and specialty vehicles (street sweeping vehicles, garbage trucks). In total this market counts roughly 30 thousand vehicles, of which buses and trucks are by far the largest fuel consumers. Alongside this, these two applications have been tested for which data are present, and will therefore be the main focus of the HDVs market. Coincidentally, both these applications account for approximately 58 thousand kilometres per year.

HDVs such as trucks and busses are currently not commercially available as standard products. Various international test programmes have documented their findings on fuel consumption with large variations. The HyFleet-CUTE program mentioned a consumption of 22 kg H<sub>2</sub> per 100 km for their buses, whereas test programs in London managed between 8-10 kg per 100 km. This scenario therefore assumes the average of 15 kg per 100 km for HDVs. The province of Noord-Holland has three bus operators active in several concessions, namely GVB on Amsterdam city level, EBS in Waterland and Connexion operates all regional bus transport. EBS operates 38 lines with approximately 200 buses, Connexion close to 700 buses regionally, and in Amsterdam City the GVB operates around 215 buses (Interview Ed

Koelmeijer, 2016). Aside from buses, Noord-Holland operates approximately 8 thousand trucks and 7 thousand tractor-trailer combinations are registered, resulting in 15 thousand trucks in total (CBS, 2014).

Buses and trucks are by far the largest fuel consumers in terms of numbers and kilometres driven, so the expected market demand for hydrogen for HDVs is based on these applications. This makes a total of approximately 16 thousand HDVs in Noord-Holland, meaning 6,500 prospective fuel cell HDVs.

**Table 19 Approximation of future hydrogen demand in Noord-Holland**

	<b>PH2 Market NH</b>	<b>Km/yr.</b>	<b>Kg/H2/100km</b>	<b>PH2 ton/yr.</b>
<b>Light Duty Vehicles</b>	500,000	13,500	1	65,000
<b>Heavy Duty Vehicles</b>	6,500	59,000	10	35,000
				100,000

## 4.2.2 Groundings

This chapter focuses on the requirements and indicators in the region. The relevant available resources are explained, required physical and institutional infrastructures and regulation are assessed based on model and the current situation of the case study. The chapter starts with policies on national and regional level, followed by the institutional infrastructure aimed at hydrogen mobility development. The remaining elements such as technology and regional resources are explained, and the chapter finalizes with the economics related to technology and resources.

### 4.2.2.1 Regulation

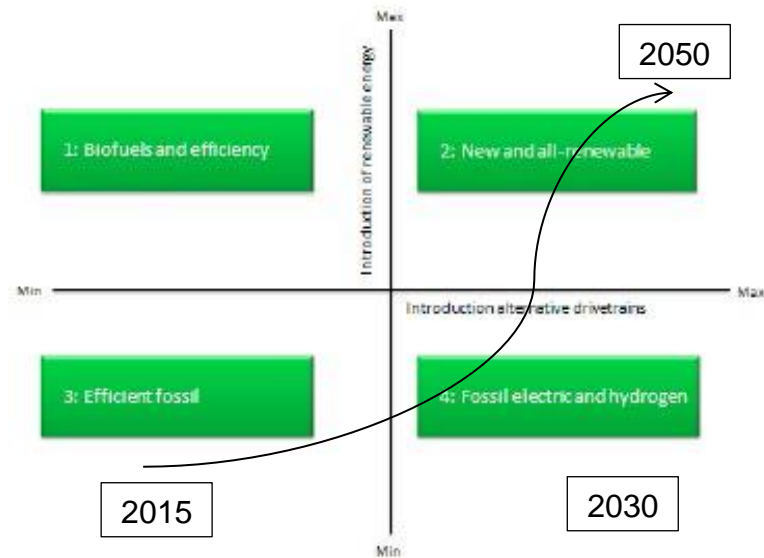
#### 4.2.2.1a National policy

In 2013 the ministry of Economic Affairs of the Netherlands presented the ‘Energy Agreement for sustainable Growth’, aiming at an energy transition towards 2050. For the sector mobility and transport, the agreement states to contribute 15 to 20 PJ to total energy savings, a maximum of 25 Mton of CO<sub>2</sub>-equivalent emission reduction, and as of 2035 all newly sold personal vehicles should be capable of driving zero-emission. This has led to a long term vision for a sustainable fuel mix published in 2014, established with over one hundred organizations, setting out concrete goals and actions in order to stimulate public-private partnerships known as ‘Green Deals’. (SER, 2014).

Green deals are multi-year collaborations, are set up between businesses, civilians, organisations and governments to develop sustainable initiatives together and to remove barriers for development on national and state level. Three (potential) Green Deals are relevant for hydrogen mobility development, being zero emission city distribution, zero emission bus transport and launching customers for taxis and city cleaning operation (RVO, 2013; SER, 2014). As part of the second Green Deal, Rijkswaterstaat has recently set up a subsidy program for HFC buses, so that for 5 projects that foster at least 2 FCE buses 850,000€ can be made available (Kuijpers, 2014). A recent example of a project that has successfully established a Green Deal is Industrial Symbiosis (utilization) of by-product hydrogen in the Rotterdam area. Chemical company Dow Benelux have agreed to distribute by-product hydrogen to fertilizer multinational Yara and bromine company ICL-IP Terneuzen via an existing pipeline in the area operated by the Gasunie. This makes this research evidently interesting to pursue.

Hydrogen receives special attention, as the European Commission has requested an action plan for hydrogen infrastructure before 2020 (SER, 2014). Aside from the various benefits related to hydrogen and mobility, the developed report proposes several scenario's and the preferred route towards the transition goals of 2050 (scenario 2, drive trains and renewable energy is widely introduced). The preferred and most likely route is via scenario 4: ‘fossil electric and hydrogen’. This scenario is referred to primarily as a transition scenario, where electrification in mobility increases, and electricity and hydrogen are produced centrally in large part from

fossil sources (SER, 2014). As by-product hydrogen has coal as an input, it is considered a fossil source. This scenario thus places by-product hydrogen from fossil sources as a transitional source, and can be positioned somewhere between the years 2015 and 2035.



**Figure 10 Preferred route towards transition goals regarding drive trains and energy sources (SER, 2014)**

The ministry of Infrastructure and Environment views its role in the development of hydrogen technologies in mobility as one to create the right preconditions, to remove governmental barriers and insecurities, to research technical safety questions and to explore how hydrogen mobility can be developed in the Netherlands (Ministerie van Infrastructuur en Milieu, 2014).

#### 4.2.2.1b Noord-Holland Provincial policy

The province of Noord-Holland is governed by a council chosen every four years by the public. Most importantly, the province is responsible for the concessions of regional public transport in three defined areas, namely the NHN area, Haarlem/IJmond and Gooi en Vechtstreek areas. Furthermore, they are responsible for improving air quality in accordance with the European Guidelines, issuing licences to heavy industries and enforcement, for waste treatment and sustainable area development. . The province can support business by providing infrastructures, knowledge and innovation and education to provide qualified personnel (Provincie Noord-Holland, 2016). The Stadsregio Amsterdam (SRA) area (also shown in Figure 11) can be categorized as a supra-local body which is installed by the national government. Traffic and transport is part of their responsibilities, and are the concession granter for public bus transport concessions in Amsterdam and the surrounding areas (Stadsregio Amsterdam, 2016).



Figure 11 Concession areas under Province and supra-local body jurisdiction (source: Provincie Noord Holland, 2016)

Mainly, in accordance with the European Guidelines of 2008, the provinces are licensed to the enforcement of licences to heavy industries, waste treatment and sustainable area development. Also, the province can support business businesses by providing infrastructures, knowledge and innovation and education to provide qualified personnel (Provincie Noord-Holland, 2016). Alongside this, the province has the ability to steer towards implementation of zero-emission transport by including regulation of emissions to public transport concessions (NWP meeting, 2016). Furthermore, in order to create room for development and innovation with regard to zero-emission mobility, during the run time of the concession it is compulsory for companies to cooperate to potential pilots in the region (Programma van Eisen NH, 2016).

A HRS in the province can be either built new, moved or an existing one can be changed on public domain. In all cases, environmental permits as well as exemption is required in accordance with the province. In the case of concessions provided by

the provincial government, boundary conditions are stated. However, the company holding the concession is responsible for the purchase, construction and maintenance of new types of zero-emission technology they choose to implement. This included the deals necessary with third parties for construction of new infrastructure and the related permits. The province cannot guarantee a permit for a novel zero-emission infrastructure and states that it is not their responsibility. They can however facilitate the process of permitting as much as possible

#### 4.2.2.2 Institutional capacity

In the province of Noord-Holland, there is one public research institution present, ECN, that focuses on various renewable energy technologies. The institution houses a department that focusses specifically on hydrogen and fuel cell technology. The capacity was however reduced due to the growing focus of battery electric vehicles in the region. However, the institute has many international partnerships regarding European research projects, and publishes their findings openly (Denys and Barten, 2009; ECN, 2016). In an important collaborative article where ECN has participated, they stress the concerted effort and network infrastructure needed with all stakeholders involved in hydrogen market preparation and early rollout. Aside from publications, ECN is active in the national collaboration known as the National Hydrogen Platform.

### National Hydrogen Platform – the Netherlands

In order to investigate potential barriers and opportunities while increasing collaboration between organisations, knowledge institutions and government a National Hydrogen Platform is being established and presently active. Together they

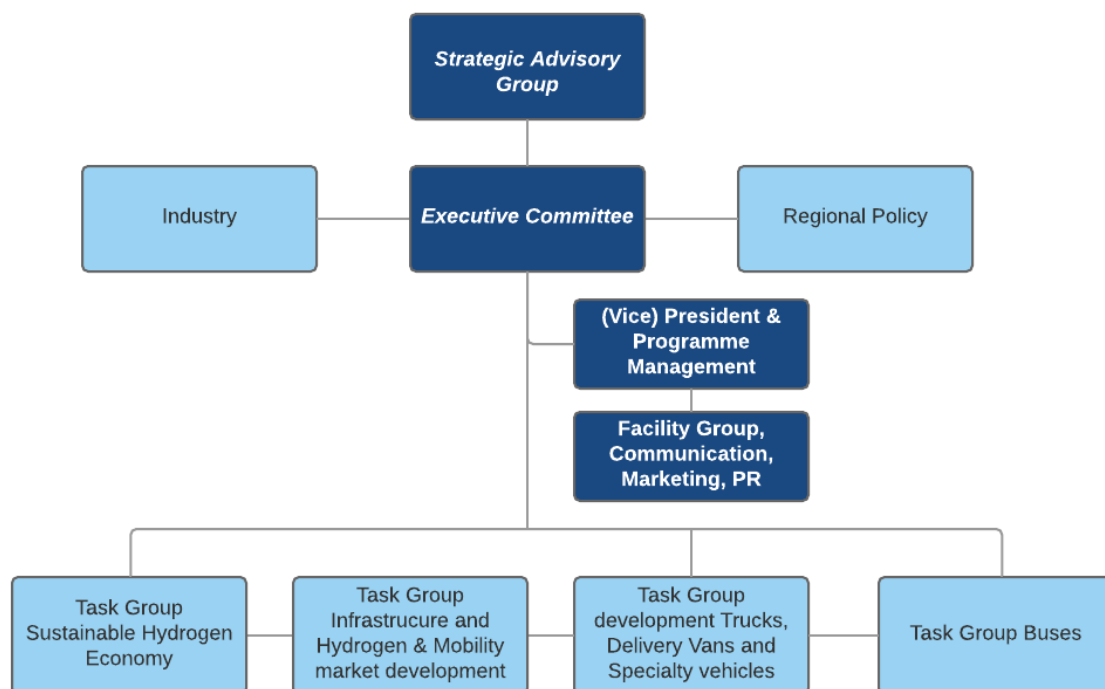


Figure 12 Organigram of the National Hydrogen Platform developed by the author

propose to professionally organise the establishment of a hydrogen supply chain from production to end-user. Furthermore, the aim is to transparently build a knowledge base around the topic of hydrogen together with academic institutions. The platform also acts as a collocutor with the national government regarding the stimulation and introduction of hydrogen applications for mobility and energy (General assembly National Hydrogen Platform, 29-09-2016).

In general, the platform holds general periodic meetings 2-3 times a year. Together, the strategic advisory group, executive committee, communication teams and others marked in dark blue safeguard the mission of the platform and monitor the potential Green Deals and other overarching boundary conditions. They are responsible for structurally upholding contacts with politicians (national and regional), contacts internationally and with industry and knowledge institutions. Furthermore, they diffuse the gained knowledge through their website and emails, and act as the ambassadors of the National Hydrogen Platform. As the operations of the various task groups are intertwined but act separately, they are also responsible for the creation of synergies between the various Task Groups. Government officials, research industries, consultancies and industry stakeholders are present in these groups (Assembly National Hydrogen Platform, 29-09-2016).

#### *Task Group Sustainable Hydrogen Economy*

The activities of this task group concern exploring the possibilities and creating a vision for the hydrogen economy in the Netherlands using strategic analyses. This includes the current and future technologies, and ultimately creating a strategy for moving towards sustainable sources, with a short term focus on fossil based hydrogen, ultimately transitioning to green hydrogen from renewable sources. This group also focuses on policies and related hurdles regarding the introduction and fiscal stimulation and safety requirements.

#### *Task Group Infrastructure and Hydrogen & Mobility market development*

The main task is to research the provision of hydrogen infrastructure in order for the Netherlands to become one of Europe's launching markets for FCEVs. The main activities include the admission and commitment to European funding, development of a roll-out and investment program and cooperation between neighbouring countries Germany, Belgium and Luxembourg. This includes specific locations and the local business cases. Also, they research matching supply and demand and the organisation of the initial fleets of FCEVs, and concentrate on propositions towards FCEV manufacturing companies.

#### *Task Group development Trucks, Delivery Vans, and Specialty Vehicles*

This group is assigned to create consortia related to these specific vehicles of original equipment manufacturers (OEMs) and potential users. The focus in particular

is on auxiliary power units, forklifts in distribution centres, fuel cell trains and canal boats.

### *Task Group Buses*

As part of the European commercialisation program to reach up to 500 FC buses in Europe, this task is focused for realisation in the Netherlands in line with ambitions of the Zero Emission busses Foundation and the 'motion of Veldhoven' from the government. The main focus is to define, design and work with a consortium of stakeholders to realise an investment and roll-out program.



Figure 13 Official partner of the National Hydrogen Platform (<http://nationaalwaterstofplatform.nl/>)

As shown in organigram in Figure 12, the platform aims to involve regional policy makers and recognizes the importance of doing so. However, from participating in various general assemblies and Task Group meetings, it was found that several provincial and municipal members participate (provinces of Brabant, Gelderland, Zuid-Holland). However, policymakers from the province of Noord-Holland have ended collaborations and do not attend any meetings. This can be regarded as an important gap in the institutional infrastructure for developing regional hydrogen mobility.

#### *4.2.2.3 Natural resources*

Natural resources can refer to many different inputs. As mentioned in the problem statement for the case study, TSIJ has found it can possibly separate hydrogen from a waste gas stream known as Coke oven Gas (COG) from coke production, an important input for steel manufacturing. A more detailed description of the specific characteristics of this process is presented below. The initial focus of this research was on the possible hydrogen separation of this by-product stream in relation to industrial symbiosis, however during the research it was found there is an additional existing source of hydrogen currently available from a Steam Methane Reformer installation.

In order to provide more detail on the hydrogen resources at TSIJ and the requirements, several indicators had to be added as these specifications were not included in the developed model. Requirements of by-products are determined by the eventual applications and by the possibilities for the source in terms of treatment and upgrading. In his article, Lowe (1997) explains the importance of the composition and quality of the flows of by-product materials and energy, the amounts, distribution of flows over time (steady, periodic, episodic, irregular). The indicators described in the Porter diamond are quality, quantity and cost. Combining the two fields leads to by-product requirements described by the indicators cost, quality, quantity and distribution over time, and can act as a guideline for assessing hydrogen requirements.

## Quantity

### *On-site Steam Methane Reforming*

As mentioned, with regard to hydrogen there are two main sources of (by-product) hydrogen present at Tata Steel IJmuiden. On-site, TSIJ has a small scale hydrogen producing Steam methane reformer (SMR). At full capacity, the SMR unit is able to produce approximately 330,000 kg of hydrogen per annum. However, this hydrogen is partially used for internal processes. This is about half of the total capacity, resulting in an overcapacity of approximately 160,000 kg per year. The portion currently utilized is on an on-demand basis, meaning it cannot be regarded as an available source. However the quality of this hydrogen does not meet demand of FCEVs, for which an extra purification step will need to be installed.

### *By-product hydrogen from Coke Oven Gas*

The main potential source of by-product hydrogen from coke oven gas at Tata Steel IJmuiden. The total waste stream of gas is 14 PJ, of which the gas mixture is shown in the following section. Currently, 12 PJ of coke oven gas is used for its heating value in internal operations, of which approximately half is used for heating a coke plant and the other half for blast furnace heating. The remaining 2 PJ is led to an adjacent power plant for electricity generation. Together, Tata Steel IJmuiden and the energy company have a “tolling agreement”, meaning the ownership of the coke oven gas and electricity is Tata Steel IJmuiden while paying a fee for the electricity production. The gases are delivered by Tata Steel IJmuiden and all the electricity is returned to steel company, while electricity surpluses are sold to the grid by the energy company. As there are limitations at the power plant, 2 PJ of coke oven gas is available per year, making this an interesting flow option. The hydrogen content of the coke oven gas is as high as approximately 58Vol%, which in volume is the largest component (Table 21). By using pressure swing adsorption as a separation technology (more detail in the technology section), 77,5% of the hydrogen from COG can be extracted and purified, corresponding to 4.829.587 kg of hydrogen per year. As the focus of this research is more on cluster development, this figure will be rounded to 5000 tonnes/yr.

Separation of hydrogen molecules from the total flow of 14 PJ with the mentioned hydrogen content is also technologically possible. However, the company is currently heavily reliant on this heat source for which technology is in place and is expected to remain so. Nonetheless, separation and purification of the total hydrogen content can potentially be up scaled to an annual production of over 35.000 tonnes of hydrogen.

**Table 20 Possible hydrogen source pathways present Tata Steel IJmuiden**

<b>SMR pathway</b>	Appx. 160.000 kg/year
<b>2 PJ pathway</b>	Appx. 5000 tonnes/year
<b>14 PJ pathway</b>	Appx. 35.000 tonnes/year

#### **4.2.2.4 Available technology and infrastructure**

This section makes a distinction between technology and infrastructure, as elements from both categories can be regarded as being technological. In this case, technology starts and stops at a decoupling point, what happens in between is referred to as infrastructure. Therefore, the technology explained in the section will introduce the pressure swing adsorption technology needed for hydrogen separation up to the point of storage, followed by a section on infrastructure, in finally an explanation on the current situation of hydrogen refuelling stations.

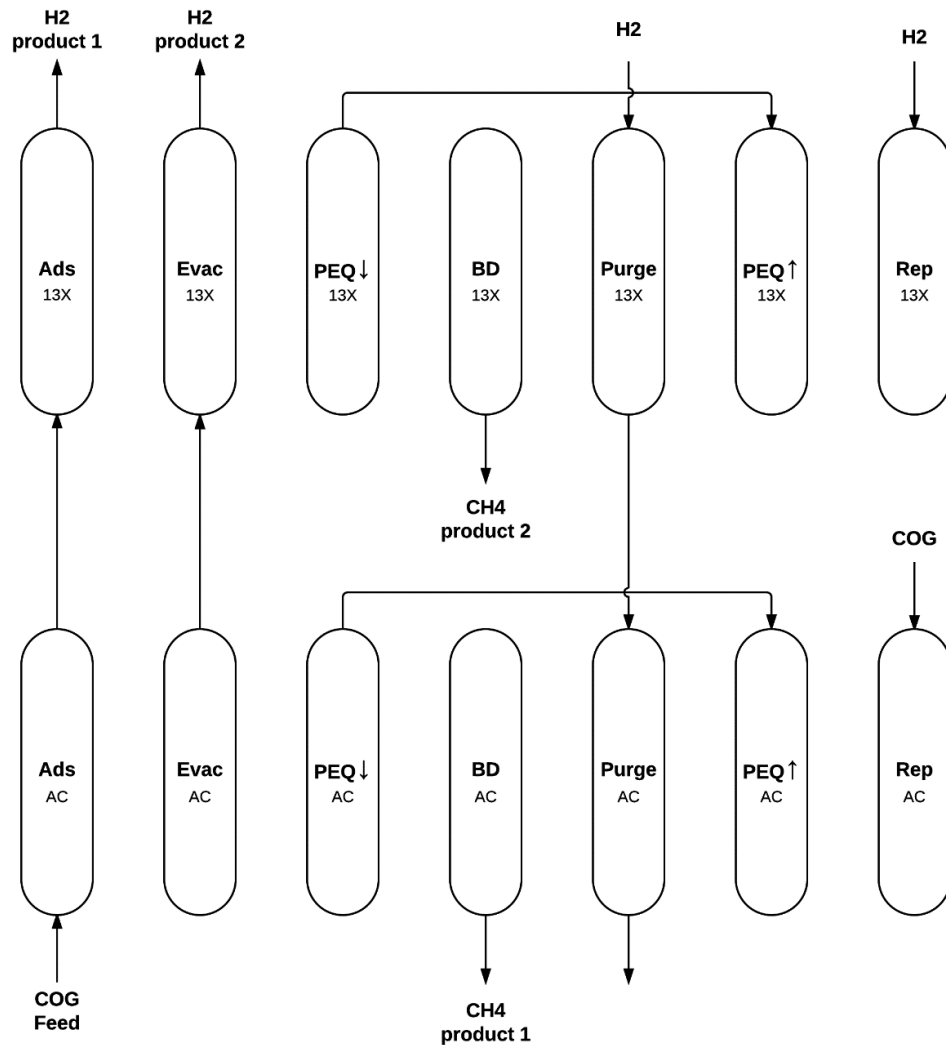
##### **4.2.2.4a Pressure Swing Adsorption**

In order to recover the hydrogen and reach the required purity levels, separation by adsorption and desorption can be applied. Adsorption is the reversible binding of molecules and atoms from the gaseous or liquid phase on surface on surfaces, mostly of highly porous adsorbent media (Ullman, 2007). Separation technologies are based on different affinity of gases for an adsorbent material, where the effectiveness of adsorption depends mostly on volatility and polarity of the feedstock components, in this case COG. As hydrogen is a highly volatile and non-polar molecule, therefore it adsorbs in very small amounts compared to other gases found in COG. According to Chauvel and Lefebvre (1989), this makes adsorption processes very applicable to hydrogen.

Several adsorption processes exist, however studies at Tata Steel IJmuiden by van der Veen (2013) and Ramani (2016) have identified pressure swing adsorption to be preferable choice. Depending on several factors such as partial pressure of a gas component, composition, adsorbent material and temperature at which it operates a certain force acts between gas molecules. Pressure Swing Adsorption (PSA) alternates the pressure in order to perform adsorption and desorption. Various organisations have installed PSA technology, including a Tata Steel plant in Jamshedpur in India and Nippon Steel in Japan.

A PSA cycle follows a number of steps shown and explained in Appendix B. As briefly mentioned above, Ramani (2016) an optimal multi-bed PSA cycle process for hydrogen separation from COG using a mathematical modelling approach. The outcome is a set of four two-columned pressure swing adsorption cycle with counter-

current purge and repressurisation with one pressure equilibration step in order to produce high purity hydrogen (> 99,999%) (Ramani, 2016) shown in Figure 14. The various steps of pressure swing adsorption are explained in more detail in Appendix B.



**Figure 14 Pressure Swing adsorption designed for hydrogen separation from COG at Tata Steel Ijmuiden (Ramani, 2016)**

## Quality

One of the major influences in the hydrogen gas industry is the quality of hydrogen. Hydrogen gas can contain a range of substances depending on the source, so quality is defined in terms of purity. Required purity can relate to both the purity reached by separation technology and the required purity demanded by the fuel cell market. However, the end applications in the market thus dictate the type of separation technology required.

As shown in the technology section, the current use of COG gas is subject to a COG cleaning chain when it leaves the coke oven plant. 2 PJ of COG is directed to a power plant in the region and the remaining amount is used for various heating purposes. After cleaning, the gas has a wide variety of components. The composition of the COG and the volume percentage are shown the table 21 below (Spits & Jägers, 2013).

**Table 21 Composition of coke oven gas at Tata Steel IJmuiden**

Formula	Component	Content after cleaning <sup>a</sup>	Molar mass
		Volume %	g/mol
H <sub>2</sub>	Hydrogen	58%	2
CH <sub>4</sub>	Methane	24%	16
CO	Carbon monoxide	6%	28
N <sub>2</sub>	Nitrogen	8%	28
C <sub>2</sub> H <sub>4</sub>	Ethylene	2%	28
C <sub>6</sub> H <sub>6</sub>	Benzene	0%	78
CO <sub>2</sub>	Carbon dioxide	1%	44
C2-C5	Hydrocarbons	0%	44
C <sub>2</sub> H <sub>6</sub>	Ethane	1%	30
O <sub>2</sub> and AR	Oxygen and Argon	1%	35

As shown, the COG has a high volume percentage of hydrogen. However, many other components are present which can be harmful to the potential application. The extent to which components harm the end use application differs greatly per component. Therefore the required amount for harmful substances is much lower than for those less harmful.

Typical PSA purities range from 99 to 99.999% (Miller and Stöcker, 1989), however it is argued that purities over 99.99% are very difficult to achieve (Bermudez, Arenillas, Luque, Menendez, 2013). As mentioned, the required level of hydrogen purity is of major importance for the applications, and define the minimum purity required. When looking at applications, these purity requirements may differ. In various markets and clusters it is essential that standards are set, for which organisations such as International Standards Organisation (ISO) exist. The status and requirements will be handled in more depth under *standards* as part of the chapter on access to local markets. However and as can be concluded from the standards chapter, the required quality is somewhat scattered and difficult to uncover. Nedstack, a fuel cell manufacturer based in the Netherlands posted a product data sheet incorporating the maximum allowable concentrations of impurities for fuel cells used in various applications, including mobility and auxiliary. FCV's require over a 99% purity level, which a PSA system is able to deliver.

**Table 22 Maximum allowable concentration of impurities for fuel cell technology (Nedstack, 2016)**

Impurity	Max allowable concentration	Units
O <sub>2</sub>	0,05	% Volume
N <sub>2</sub>	0,05	% Volume
CO <sub>2</sub>	0,1	% Volume
NaOH	0,1	ppmv
CO	0,2	Ppmv
Cl <sub>2</sub> +ClO <sub>2</sub>	1	Ppmv
Hg	0,004	Ppmv
Total Sulphur	0,004	Ppmv
Formaldehyde	0,01	Ppmv
Formic Acid	0,2	Ppmv
Ammonia	0,1	Ppmv
Total halogenated compounds	0,05	Ppmv
Particles	1 µg/l at 20 Celsius, 1 atm	

## Hydrogen flow

An important factor within industrial symbiosis and by-product utilization is the analysis of the distribution over time, as this influences the compatibility of input and outputs and the security of supply to potential customers. The demand for hydrogen can indeed fluctuate on the short and long term, making a secure supply and possibilities of storage at fuelling location an important factor. The partial load behaviour of separation technologies must be considered, and the throughput of a PSA system can be varied between 30 and 100% by adjustment of the cycle time (Miller and Stöcker, 1989). A lower throughput results in a discrete flow, making it intermittent and not constant. Generally, PSA systems are discrete in operation, but by using a series of four columns they can be made continuous which results in a constant flow of hydrogen, as the adsorption between the columns marked in yellow overlap as shown in Figure 15 (Ramani, 2016). This section will not deal with the technical aspects and design of the adsorption process of the PSA system, but in terms of security of supply and distribution of time it is important to note that a continuous supply is possible.

Duration (sec) / Column No.	50	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400
1	Ads															Evac	PEQ↓	BD	Purge					PEQ↑	Rep			
2	Ads	Evac	PEQ↓	BD	Purge					PEQ↑	Rep				Ads													
3	Ads								Evac	PEQ↓	BD	Purge					PEQ↑	Rep				Ads						
4	Purge		PEQ↑	Rep			Ads														Evac	PEQ↓	BD	Purge				

**Figure 15 Four column design of the pressure swing adsorption system allowing for a continuous flow (source: Ramani, 2016)**

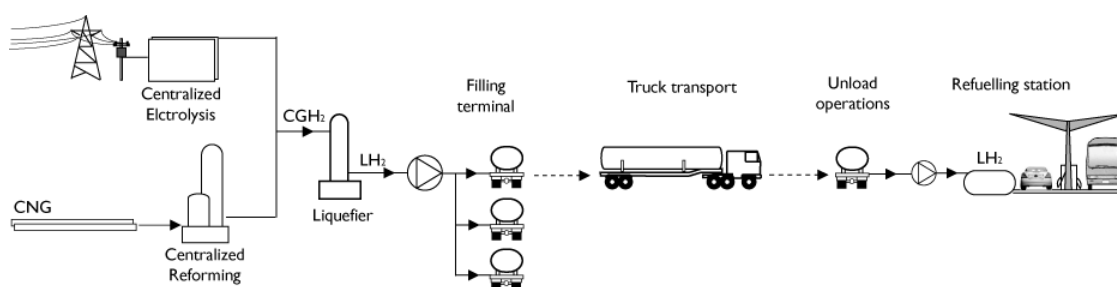
In a MATLAB simulation study, Ramani (2016) succeeded in modelling and simulating a PSA technology for hydrogen separation and purification from COG and determining the best possible process performance in terms of purity and recovery of hydrogen. The outcome led to an optimised 14-step multi-bed PSA cycle allowing recovery of hydrogen purity level that meets the standards for fuel cell technology at a continuous flow rate. Subsequently, this configuration leads to the highest possible security of supply.

#### 4.2.2.4b Distribution infrastructure

Aside from the production mode of hydrogen, the other key (cost) determinant for supplying hydrogen is the distribution (Rösler, Bruggink, Keppo, 2011). The requirements for the physical infrastructure for the distribution of hydrogen are determined according to the chosen delivery pathway. Hydrogen sources can range from decentralised production (such as on-site electrolysis) to centralised production (such as central SMR). As the by-product of TSIJ is produced centrally, necessary physical infrastructure will only be taken into account for such distribution pathways.

The main indicators for determining the costs and thus the most interesting mode of distribution are the transported hydrogen flow and the distance over which the hydrogen would need to be transported (Johnson, Yang, Ogden, 2008). As the most economic means of transportation is determined by these parameters, it has led to the main options being either through a pipeline or transportation by trucks, with the hydrogen either in liquid or gaseous forms (Rösler et al., 2011).

The distribution infrastructure for a centralized production mode and transportation to a HRS by truck with hydrogen in liquefied form is shown in Figure 16. The main components are a liquefier, liquid pumps, cryogenic storage tanks, filling terminals, transportation trucks and unload operations. These components and related costs are explained in more detail under the economics of infrastructure section.

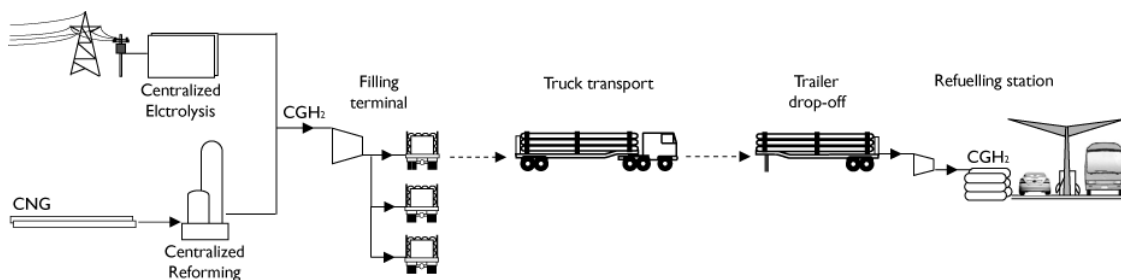


**Figure 16 Liquefied truck distribution infrastructure (source: Rösler et al., 2011)**

As shown in the figure, the first step is the liquefaction of the hydrogen. For liquefaction of hydrogen, the temperature is lowered to  $-253^{\circ}\text{C}$ , for which the electricity required is about 35-43 MJ el/kg  $\text{H}_2$ , which is a substantial amount. This results in 75% of total cost related to the cost of electricity. Furthermore, the fixed costs related to the investment needs increase considerably due to the liquefier. In this regard, the main costs are not related to the distance of distribution but mainly to the process, liquid hydrogen trucks become most economically attractive over long

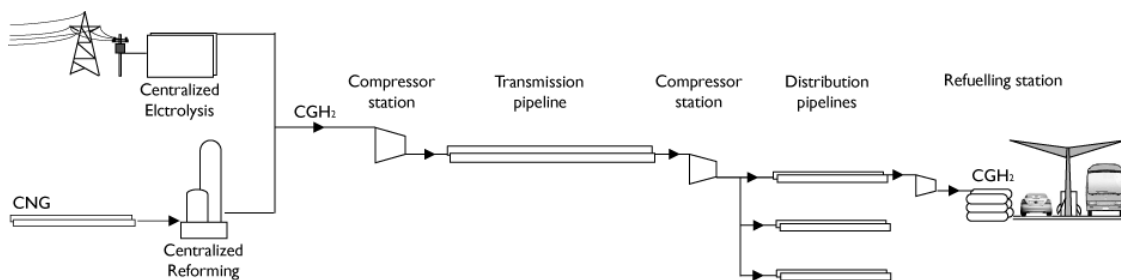
distance transportation. Subsequently, the liquefaction costs decrease as the amount of hydrogen to be transported increases, this pathway becomes competitive when both transported over long distance in larger volumes .

The second distribution pathway is by truck in compressed gas form (Figure 17). The main components are gas compressors, filling terminals, trucks with tube trailers and a trailer drop-off location (more detail on separate components is given in Table 26 in the economics chapter 4.2.1.6). As the energy density of compressed gas is much lower than liquefied hydrogen, the amount of hydrogen transported per truck is relatively low. This leads to relatively high variable costs, however the required investments are lower than other options which makes gaseous truck distribution interesting for low volumes (<8000 kg H<sub>2</sub>/day for longer distances) and low distances (<150 km for larger volumes) (Rösler et al., 2011). As the flow of the transported hydrogen increases, the other distribution pathways quickly become more interesting as they benefit more from the increased volume.



**Figure 17 Compressed gas truck distribution infrastructure (source: Rösler et al., 2011)**

The final distribution pathway discussed here is by pipeline. As shown in Figure 18, the main components for this pathway are a compressor station, a transmission pipeline followed by another compressor station, several distribution pipelines which lead are compressed and finally stored in compressed gas storage tubes of vessels. The route of pipelines are generally seen as having high investment costs which increase linearly with added length of pipe, making it is especially suitable for large hydrogen flows. Furthermore, the larger the flow, the longer the economically lucrative distance for pipeline hydrogen transportation becomes (Johnson, Yang & Ogden, 2008).



**Figure 18 Pipeline distribution infrastructure (source: Rösler et al., 2011)**

#### 4.2.2.4c Hydrogen Refuelling Stations

At hydrogen refuelling stations (HRS), hydrogen is supplied to the application, which can either be a mobility, home or stationary application. In order to prepare the hydrogen mobility market, the development of market standards is essential. Subsequently, two types of HRSs are currently being developed:

- 350 bar HRS for forklifts, buses, range-extender type road vehicles in the 20 – 200 kg/hour capacity range
- 700 bar HRS for full power H2 road vehicles in the 80 – 1000 kg/day capacity range

Currently and mainly stemming from German H2 Mobility initiative in 2010, four different HRS sizes are being considered. A very small station (80 kg/day), small (212 kg/day), medium size (420 kg/day) and stations that are considered large (1.000 kg/day). Especially regarding the market uptake of FCEVs, HRSs need to be upgradable in order to align with the growing demand by adding storage or compression capacity. This however is currently not always the case, especially increasing the capacity from very small stations to larger HRSs. Table 23 provides an overview of the number of HRSs the various delivery pathways of TSIJ are able to deliver to. Note that these numbers are based on the H2 Mobility project and are related to 700 bar stations for passenger cars.



Figure 19 Picture of a hydrogen refuelling station

	Very Small HRS	Small HRS	Medium HRS	Large HRS
<b>average output/day (700 bar)</b>	56 kg	168 kg	336 kg	700 kg
<b>Max output/day (700 bar)</b>	80 kg	212 kg	420 kg	1000 kg
<b>Number of cars per station (approximate)</b>	100	400	800	1600
<b># stations based on average output/day with H2 from TSIJ</b>				
<b>SMR</b>	8	2	1	0
<b>2 PJ</b>	232	77	38	18
<b>14 PJ</b>	1700	570	285	136
<b># stations based on max output/day with H2 from TSIJ</b>				
<b>SMR</b>	5	2	1	0
<b>2 PJ</b>	162	61	30	13
<b>14 PJ</b>	1187	448	226	95

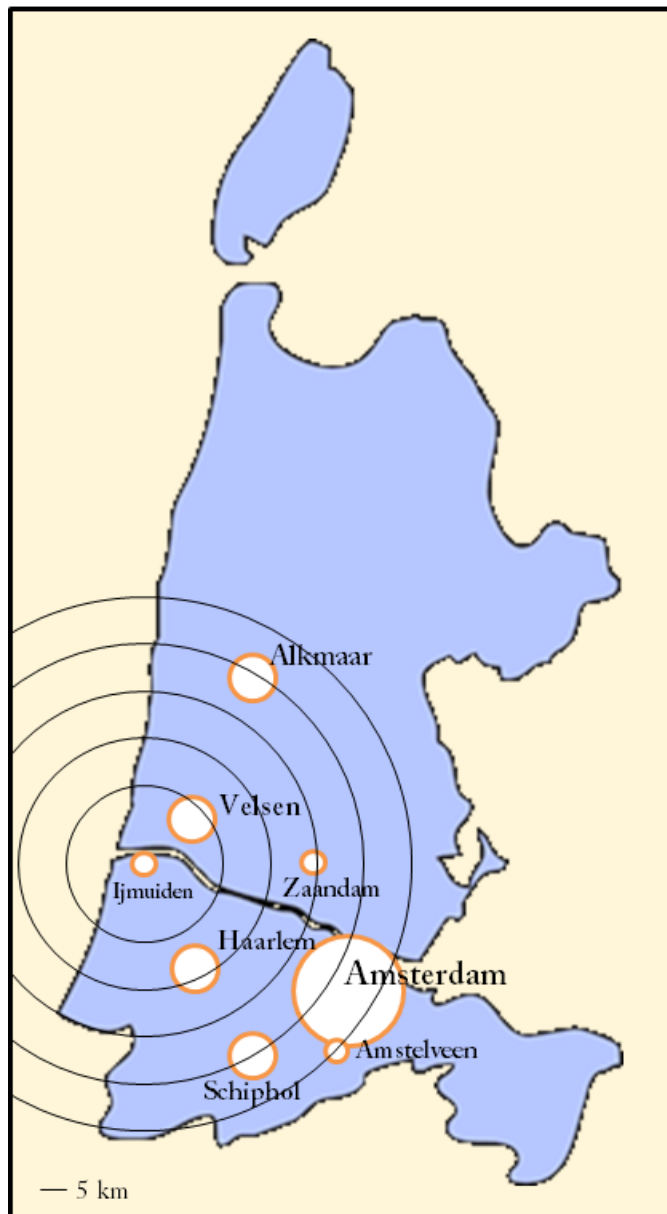
Table 23 Amount of HRS capacity per distribution pathway (source: IEA & HIA., 2015)

#### 4.2.2.5 Strategic geographical location

Figure 20 shows a plot of geographically proximate urban areas with the cluster hub Tata Steel IJmuiden as a centre point, situated in IJmuiden. Every grid line represents 5 kilometres, which shows there are several dense urban areas in the region all within 30 kilometre distance to the hub. These areas include the cities of Velsen, Alkmaar, Zaandam, Haarlem, Amsterdam and Amstelveen. Furthermore, Schiphol airport is at approximately 20 kilometres distance from the hub.

From the viewpoint of the Tata Steel IJmuiden hub, an interesting region is that of Schiphol airport, Haarlem and Amsterdam, located in the south east direction of the hub. This area, especially regarding Schiphol airport is geographically a relatively small area, which is favourable for distribution (Interview Jaap Oldenziel, 2016). The reason for this is a minimal necessity for infrastructure and fuelling stations for a relatively large hydrogen mobility market (Interview Jaap Oldenziel, 2016). Schiphol is an interesting local market due to

several reasons. It is a market with a wide variety of possible hydrogen applications and has a large range of operational fleets in the area. Schiphol airport should be viewed as a real estate and infrastructure company which provides the necessary conditions of airline companies and so-called fuel handling business to operate (Interview Ed Koelemeijer, 2016). Interesting hydrogen applications consist of fleet vehicles with high power requirements and long operating time commonly known as heavy duty vehicles (Interview Ed Koelemeijer, 2016). These consist of buses, filling cars, Ground Power Unit's and freight units. Other applications primarily run by the handling businesses are baggage cars and toilet cars. Especially stationary applications such as the Ground Power units are interesting applications, as these are currently diesel generators with high emissions, creating unhealthy work



**Figure 20 Tata Steel is strategically located close to ports, urban areas and Schiphol Airport**

environments for operating staff (Jaap Oldenziel, 2016; Ed Koelemeijer, 2016). Within the platform of Schiphol, 40 buses are operational, however these are short distances, making it less interesting as a hydrogen application. Schiphol does however influence the concessions for these fleets. Transport fleets in the area largely consist of buses and taxis, where the concessions are subject to the regional government (Ed Koelemeijer, 2016). Interestingly, various companies at Schiphol have expressed interest in hydrogen, but the classic chicken and egg dilemma arises: who will build the filling station and corresponding infrastructure (Ed Koelemeijer, 2016). Airline company Schiphol currently owns and operates its refuelling stations.

Along the two parameters of distance and volume, Yang and Ogden (2008) modelled the most economic transport options for point-to-point delivery for the three distribution pathways considered above. The outcome of their computation is shown in Figure 21.

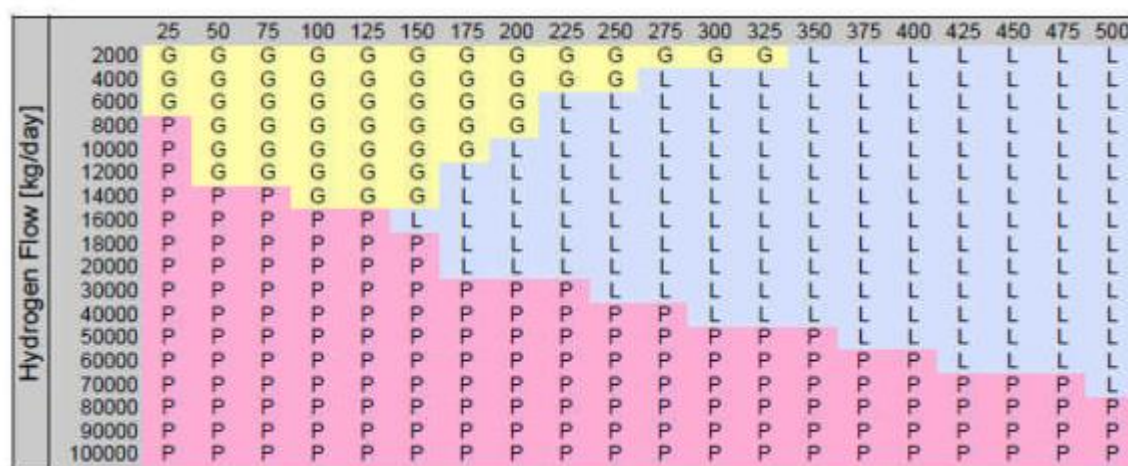


Figure 21 Economics of delivery pathways set out in transport flow in kg/day and distance in km (source: Yang & Ogden, 2008)

Overall, the graph shows that in any case of low volume, trucks are the preferred option to pipelines. From the findings it becomes clear that the distribution option of liquefied truck only becomes attractive for relative low volume at extremely high distance (275-350 km). Furthermore, the lowest economically attractive distance is >150km, starting from 16.000 kg H<sub>2</sub>/day, or >5000 tonnes per year. As shown in Figure 20, the possible markets are mostly within 30 km of the hydrogen source. This means the liquefied truck is highly unlikely to become a preferred option. During low market demand and hydrogen flows of under 8000 tonnes/day, compressed gas trucks are the desired delivery pathways.

Having a strategic location for by-product hydrogen can be assessed from various perspectives. For one and as mentioned, it should be geographically proximate to a substantial growing hydrogen market in order for it to aid in a transition. However, such a source for hydrogen within the view of a transitional model towards a sustainable hydrogen economy inclines that in a certain place in time the by-product hydrogen will be replaced. The new source would preferably be electrolysis from

wind or solar energy as these are renewable, so these sources should also be present.

In September 2014 the government organ responsible for offshore wind energy allocated several areas for offshore wind energy to be built. In order to reach realisation, the areas are tendered in order for various initiatives to compete. As shown in the Figure 22, two offshore tender areas off the coast of Noord-Holland will be opened, both with a capacity of 350 MW to reach a total of 700MW. Furthermore, from a political standpoint, this makes the case for by-product hydrogen distribution from TSIJ increasingly interesting over the long term. Having a large potential regional hydrogen source can stimulate the uptake of necessary infrastructure which in the long run can gradually be filled with hydrogen from renewables and electrolyzers. This acts as a back-up plan, as it is unsafe to bet on one private company (TSIJ) (Interview Jaap Oldenziel, 2016).

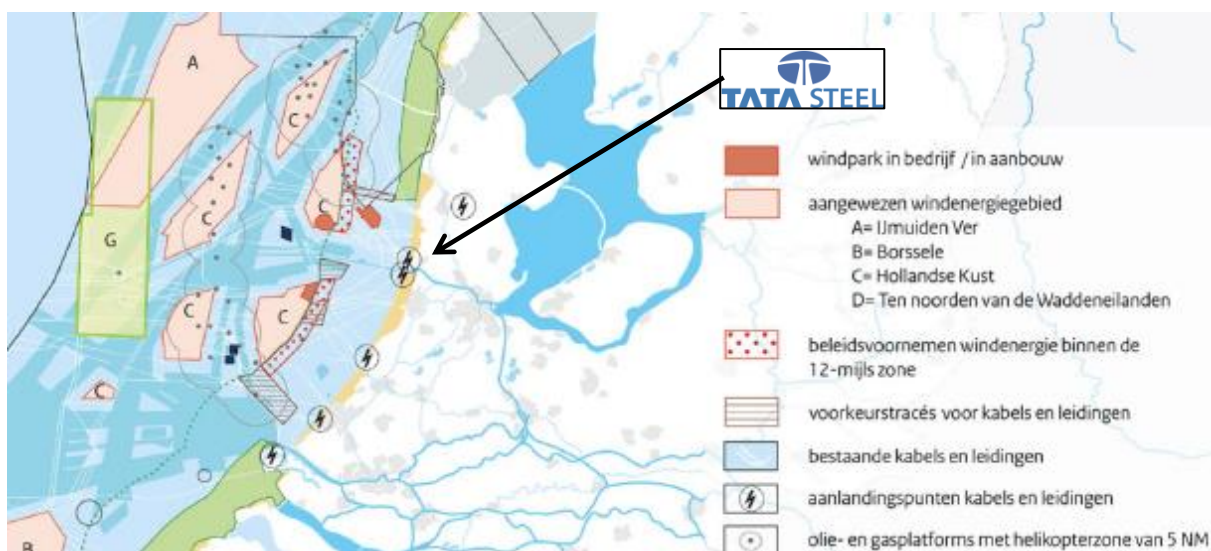


Figure 22 Plans of offshore wind parks at IJmuiden

#### 4.2.1.6 Economics of hydrogen infrastructure

##### 4.2.1.6a Market costs of hydrogen

The required or preferable cost of hydrogen can be assessed in comparison to various options. First and foremost it is important to look at projections of future hydrogen prices in general. Research performed by McKinsey & Company (2010) illustrates the pattern how the specific costs of hydrogen delivered at a pump is likely develop over time based on modelling work. This price pattern includes the various forms of hydrogen production, distribution and installation of refuelling sites, thus providing a general baseline of what the cost requirement of hydrogen should be. As shown in Figure 23 the cost of hydrogen will exceed 15 €/kg largely influenced by costs at the retail station and the low utilization (<20%) as a low number of FCEV's will be in use. When FCEV's reach an early commercial phase and utilization of hydrogen refuelling stations increases, the eventual delivery cost is expected to drop

between 7-9 €/kg, meaning it could become cost-competitive with gasoline and diesel if tax-exempted (Ball & Weeda, 2015). Eventually when the market matures, cost of hydrogen is expected to be between 4-5 €/kg, where 60-70% can be allocated to production costs and 20% and 10% are made up of retail stations and distribution respectively. From a long term perspective, achieving a positive business case for station operators compared to gasoline or diesel and make hydrogen mobility attractive, hydrogen costs at the pump will have to be below 5 €/kg. This because value added taxes, fuel taxes and retail margins need to be added (Ball & Weeda, 2015).

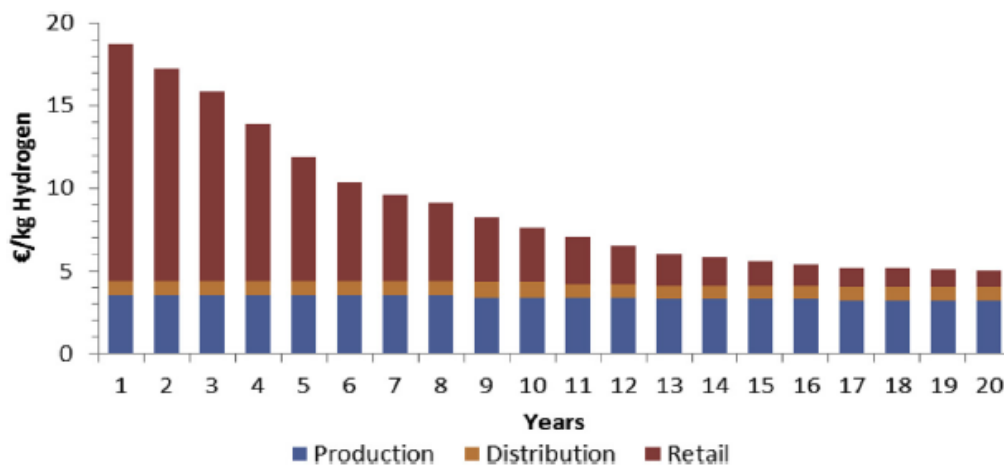


Figure 23 Projections of market cost contributions of hydrogen (source: Ball & Weeda, 2015)

As for the production cost, this is estimated to remain at approximately 3-4€/kg on average. A study by McKinsey & Company (2010) goes on to compare the production cost of various sources. According to them, production costs will range between approximately 2-5 €/kg. The higher production costs are related to electrolysis from (mostly) renewable energy sources, and the lower range related to coal gasification. The costs of technologies such as Steam methane reforming and coal gasification are expected to increase due to the rise of fuel prices and costs of future carbon capture and storage. The costs of water electrolysis however are expected to slightly drop due to improvements in efficiency (McKinsey & Company, 2010).

From this projection it can be concluded that the cost of by-product hydrogen should meet or preferably be below this average, which is predicted to stay relatively stable. It should be noted that the benchmark for pricing is location specific as taxation differs per region. Also, as by-product hydrogen is region specific (only possible where there is an existing by-product source), the choice could be made to make comparison with other regional sources.

#### 4.2.1.6b Economics of available technology

According to the owner of the Steam Methane Reformer (Linde Gas), the cost of the hydrogen delivered from this installation is approximately €2 per kg. This hydrogen does not however meet the quality requirements for fuel cell technology. Therefore, the eventual price per kg is expected to increase slightly due to necessary purification technology. This consists of the price of delivered hydrogen before being distributed outside of the company, as it is currently used for internal processes.

Regarding the pressure swing adsorption and the two different pathways (2 PJ and 14 PJ), the estimated cost price is shown in Table 24. This preliminary cost projection is based on basic economic evaluation of chemical processes (Buijs, W., 2015, April 22) and principles of process design (Towler & Sinnott, (2012). Similar to the Steam Methane Reformer, the estimations consist of production and storage of the by-product hydrogen before distribution. Perhaps the most important conclusion from this preliminary cost calculation is that both pathways are competitive with the current production cost projections shown in the previous chapter. Apparently becomes the price drop related to upscaling production, which shows that the cost price reaches approximately €1/kg below the expected production costs based on alternative production methods such as steam methane reforming.

Capacity (t/y)	Designed capacity			
	(2PJ/yr)	5000	(14 PJ/yr)	35000
1.PSA unit (M€)		8.67		31.33
2.Adsorbents (M€)		0.12		0.42
3.COG Compressor (M€)		2.25		8.13
4. H2 Compressor (M€)		4.26		15.39
5.H2 storage (M€)		3.38		12.22
<b>Total Investment (M€)</b>		<b>19</b>		<b>67</b>
<b>Variable cost</b>		<b>€/t</b>		<b>€/t</b>
1.COG fuel (€/t)		1023		1023
2.COG compressor electricity (€/t)		169		169
3.H2 compressor electricity (€/t)		241		241
<b>Total operating cost (€/t)</b>		<b>1433</b>		<b>1433</b>
<b>Fixed cost</b>				
% of Investment/capacity (€ /t)		747		386
<b>Out of pocket price (€/t)</b>		2181		1819
% Depr/Amort of I/C (€/t)		374		193
% Profit of I/C (€/t)	<b>5</b>	187	<b>5</b>	96
<b>Integral cost price (€/t)</b>		<b>2741</b>		<b>2108</b>

Table 24 Cost price of hydrogen production at Tata Steel IJmuiden using pressure swing adsorption for the 2 PJ and 14 PJ pathways (calculations based on: Buijs, W., 2015, April 22; Towler & Sinnott, 2012)

#### 4.2.1.6c Economics of infrastructure

The separate required components of the various distribution pathways mentioned above are dealt with in more detail in Table 25. Special attention was paid to the existing technologies and materials, the cost and the involved pressures as these contribute to certain requirements in different situations. The findings are however based on US sources and statistics, which leads to the cost estimates to be in US dollars.

**Table 25 Economics and specifications of hydrogen infrastructure components based on US figures (source: IEA & HIA, 2015)**

Required component	Current status
<b>Gas compressors</b>	<p>The requirements for compressors can differ in terms of capacity, pressurization, or technology employed.</p> <p><i>Pipeline transport</i> requires high flow rates at relatively low pressures (10 MPa) and compression ratios are typical. Technology typically used are high flow-rate reciprocating piston compressors or centrifugal compressors.</p> <p><i>Fuelling stations</i> require low flow rates (50-500 Nm<sup>3</sup>/h) and pressures up to 90 MPa, and loading operations at terminals generally have intermediate needs. For HRS, diaphragm compressors are typical. Currently, the cost and reliability of compressors are major barriers for commercialisation.</p> <p>The cost of an installed compressor can range from \$300,000 (small compressor) to \$1 million (large compressor).</p>
<b>Tube trailers</b>	<p>Current existing tube trailers transport high pressure gas. The most recent specifications are as follows:</p> <ul style="list-style-type: none"> <li>- Number of pressure containers: 10 tubes</li> <li>- Total volume: 24,480 l</li> <li>- Safety factor: 3</li> <li>- Design pressure: 20 MPa</li> <li>- Payload (gross): 368 kg</li> <li>- Investment cost (without rolling platform): €105,000</li> <li>- Specific costs (without rolling platform): 317€/kg</li> </ul>
<b>Pipelines</b>	<p>For large-volume hydrogen transport, pipelines are the lowest-cost option. This option is only interesting when there is a high market demand to compensate for the high investment costs.</p> <p><i>Cost:</i> Cost of pipelines vary greatly by diameter, labour cost, location and right-of-way costs.</p> <p><i>Material:</i> typically used are mild, low-carbon steels due to less concerns about embrittlement compared to higher-strength steels.</p>

<b>Compressed gas storage</b>	<p><i>Material:</i> Type 1 steel tubes are currently commonly used for compressed gas storage. Another option is Composite pressure vessels.</p> <p><i>Pressure:</i> The type 1 tubes are capable of hydrogen storage at &gt; 40 MPa, while the composite pressure vessels allow for higher-pressure of up to 100 MPa.</p> <p><i>Cost:</i> Composite pressure vessels cost more than steel vessels equivalent in size, however “per kg of hydrogen stored” costs are fairly similar. Depending on storage pressure and employed technology, cost of hydrogen storage range between \$600-1,200 per kg of stored capacity.</p>
<b>Gas cooling systems</b>	<p>According to the SAE J2601 refuelling protocol:</p> <ul style="list-style-type: none"> <li>- For 70 MPa fast-fills of gaseous hydrogen: precooling requirements are <math>-40^{\circ}\text{C}</math> in order to overcome heat of compression.</li> </ul> <p><i>Technologies:</i> currently there are several 70 MPa dispensing systems which use liquid nitrogen for precooling, another option includes refrigeration systems.</p> <p><i>Costs:</i> Depending on capacity, the typical cost for an installed cooling system and related heat exchanger range from \$50,000-150,000.</p>
<b>Liquefaction systems</b>	<p>Currently, more than 90% of the transported hydrogen in the USA is in liquefied form to reach high demands of &gt;100 kg/day.</p> <p><i>Capacities:</i> 5-40 metric tons/day</p> <p><i>Costs:</i> \$5-6/kg</p>
<b>Cryogenic storage tanks</b>	<p>Both at the production and delivery sites, storage is needed in the form of hydrogen cryogenic tanks.</p> <p><i>Capacities at HRS:</i> 800-4,000 kg</p> <p><i>Costs:</i> \$250,000-500,000</p>
<b>Liquid pumps</b>	<p>Using specially designed centrifugal pumps, liquid hydrogen can be pressurized. The most recent design by Linde Gas of a cryo-pump able to reach 90 MPa with a throughput of 120 kg/h.</p> <p><i>Costs:</i> \$50,000-300,000</p>
<b>Evaporators</b>	<p>At a given pressure, evaporators are used to gasify liquid hydrogen in the form of a series of heat exchangers. Also, controlled heat blocks can be used.</p> <p><i>Cost:</i> \$50,000-100,000</p>
<b>Dispensers</b>	<p><i>Components:</i> locking nozzle equipped to communicate with tank, ensuring right programmed fill rates, safety breakaway hoses, temperature/pressure metering, controls/safety equipment, cabinet and a card reader.</p> <p><i>Pressure:</i> Current dispensers are able to handle 35 MPa to 70 MPa.</p> <p><i>Costs:</i> Current costs of single-hose dispensers range from \$80,000-100,000.</p>

#### 4.2.1.6d Economics of Hydrogen Refuelling Stations

The capital expenditure ranges between 0.8 to 2.2 million euro's for a small to a large HRS respectively according to 2015 levels (van Hoof, van der Meer, van der Woude, 2015). All economic lifetimes are expected to be approximately 15 years, and in line with the cost projections the purchase price at the HRS after distribution are approximated at €4 per kg. An important aspect of the economics related to HRSs and the cost of hydrogen are scale economies. The costs of hydrogen decreases with increased HRS capacity and station demand, where a small station of under 100 kg/day is likely to contribute to approximately three times the price of a large scale HRS (IEA & HIA, 2015).










**Table 26 Expenditures per component and HRS type - 2015 levels (source: van Hoof, van der Meer & van der Woude, 2015)**

Expenditure component/HRS archetype	Rural basic	Urban basic		Full Service
	Very small	Small	Medium	Large
Capex (EUR million -2015 level)	0.8	1.2	1.6	2.2
Asset economic life (years)	15	15	15	15
Average hydrogen purchase price (EUR/kg)	n.a.	4.00	4.00	4.00
OPEX – fixed amount (EUR/year)	60,000	65,000	80,000	90,000
OPEX – variable amount (% of revenues)	12%	5%	5%	5%

#### 4.2.1.7 Financial incentives

The initial initiatives of deployment of infrastructure and refuelling stations require large public support and financial incentives to overcome the high investment challenges (IEA & HIA, 2015). As the fuel cell vehicle market is developing slowly, the initial business case cannot be viable to a great extent. Companies are not expected to start investing in an entire initial infrastructure. Financial incentives are needed for the initial realisation of hydrogen refuelling stations, but also aid for the annual operational costs. As the preparation phase of the market evolves into the market introduction and commercial phase, a gradual decrease in the need for public support is expected. The extent to which public support is needed, along with the profitability, reliability and sustainability of hydrogen refuelling stations is shown in graphically in Table 27 (IEA & HIA, 2015). This corresponds well to the requirements on eco-innovation, where financial support is seen as a critical element for sustainable practices.

**Table 27 Graphical representation of hydrogen refuelling station profitability and public support needed per market phase (source: IEA & HIA, 2015)**

Market phase	Public support?	HRS profitable?	HRS reliable?	HRS sustainable?
1 Demonstration	Yes 	No 	No 	No
2 Early/Precommercial	Yes 	Yes 	No 	Pseudo-sustainable
3 Commercial	No 	Yes 	Yes 	Self-sustainable

#### *Financing options involving public and private sectors*

From a series of workshops with various types of potential investors, it was concluded that none of them would invest unless the main project risks would be fully controlled by other stakeholders, such as strategic investors or the government (New Energy World & Roland Berger, 2013). The risk in this case is that the debtor has no control over the market development, which causes the main investment risk. The main potential investors are:

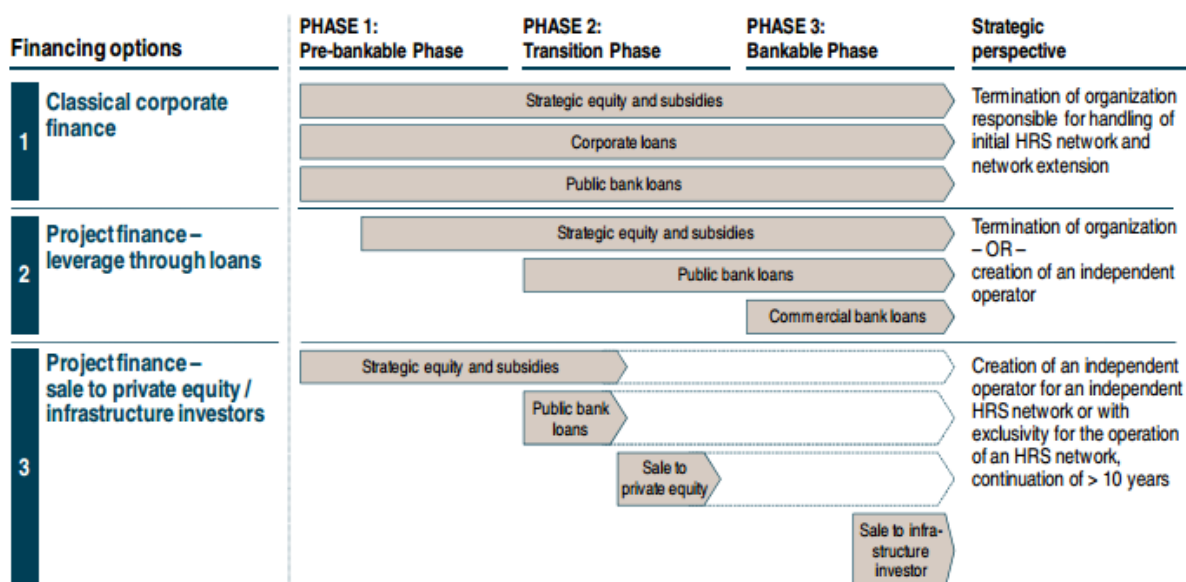
**Strategic investors** or industry stakeholders who depend on the hydrogen refuelling station (HRS) rollout to bring their products to the market. Especially when a hydrogen infrastructure and HRSs rollout part of their core business, they are expected to invest both for the short-term and long term benefits, and provide funding from the start of the project. With regard to hydrogen mobility, this group can be categorized as follows:

- Car manufacturers that aim to bring FCEVs to the market
- Oil and gas companies that operate refuelling stations
- Suppliers of HRSs that aim to grow further that small batch HRS production
- Hydrogen suppliers that are interested in developing the market

**Private sector financiers** such as commercial banks, private equity investors and infrastructure funds are expected to play a role in a later stage of HRS rollout investment. The extent of financing or their strategy may vary tremendously, based on their internal risk strategy or core business model and the horizon of their investments.

**Public and development banks** can invest depending on their policy priorities. Incentives and loans from these types of banks are case specific, but is expected to be possible and an earlier stage than commercial banks as they often have a higher risk appetite.

Figure 24 shows three types of financing options based on the previously named potential investors and the corresponding phases of bankability. In the classical corporate finance option every strategic investor finances several hydrogen refuelling stations through a mix of equity and loans, which are secured via the assets and cash flows, making leverage achievable from the start of the project. In both the second and third option (project finance – leverage through loans or with sales to private equity or infrastructure investors), a consortium is formed by strategic investors with potential public support. In the second option, debt financing from public banks becomes available, and in the final phase the consortium has access to loans from commercial banks. In contrast, in the third option a private equity investor becomes interested in financing the hydrogen refuelling station rollout after financing from public banks, and the final phase consists of an infrastructure investor may be interested in purchasing the entire consortium. This way, the infrastructure investor operates the consortium and rollout.



**Figure 24 Main financing options for hydrogen refuelling infrastructure (source: New Energy World & Roland Berger, 2013)**

In every case, the first phase (pre-bankable phase) requires joint action between governments and strategic investors, as only these parties can cover for a slow

market development. Governments play an important role in financing infrastructures with a negative initial business case, and have the ability to jump-start the roll-out, while vehicle manufacturers could be able to mitigate the FCEV uptake risk (Interview Jaap Oldenziel, 2016). In the Netherlands, Rijkswaterstaat (government organ) is responsible for the main infrastructure facilities. Currently, there are discussions as to whether underground transport (such as pipelines) should be included and allocated to the government long term budget plans (Interview Jaap Oldenziel, 2016). The same is currently the case for the water networks, where the government finances the infrastructure initially, and once the market increases in users, private stakeholders are able to pay off the debt ( Interview Jaap Oldenziel, 2016).

The three options presented above are all possible, however project finance with leverage through loans is considered the preferred route with regard to the initial phase of hydrogen refuelling station rollout. The creation of an entity or consortium that controls the development process and is able to align it with the market uptake. Furthermore, it is considered to be less dependent on individual shareholder interests and stimulate cooperation instead of all individually owning and operating various stations. Also, it makes the initial phase into a “coalition of the willing”, and creates a legal structure that can receive benefits during this first phase. Lastly, such a coalition can be a legal counterpart for the government committed to achieving promised milestones in return for public funding (New Energy World & Roland Berger, 2013).

### **European public funding**

The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) is a public-private partnership of the European Commission, industry partners and research institutions. One of the goals is put a European funding scheme in place, which will need to be supplemented by national or local programs and funds. This partnership makes European funding possible for hydrogen mobility initiatives, and interested European cities and regions are invited to join the initiative. An example is the pan European Hydrogen Mobility Europe (H2ME), which brings together 4 of Europe’s most ambitious national initiatives on hydrogen mobility (Germany, Scandinavia, France and UK) and 37 partners on developing networks of HRSs and fleets of FCEVs. The total project is expected to require €100 million, of which a Grant Agreement was signed by the FCH JU to contribute €35 million. Aside from the FCH JU, the European Union has another transport infrastructure policy that aims to connect the entire continent known as the Trans-European Transport Network (TEN-T). Until 2020, the project aims to aid in the transport network between Member States, and has a budget of €24.05 billion until 2020.

### **National public funding**

The European Fund for Regional Development (EFRO) is able to provide funding of €183,3 billion for the period of 2014-2020. One of its priorities is the development of a carbon free economy, and €500 million is expected to be available for the

Netherlands, of which €190 million is allocated for the western part of the Netherlands. The national coordination for the Netherlands is done by the Ministry of Economic affairs, and allocation is eligible under the condition that the government or private stakeholders double the amount subsidized. However, when exploring the case of hydrogen and infrastructure particularly for the Noord-Holland region, hydrogen is not (yet) on the agenda. Furthermore, the Ministry of Infrastructure and Environment engages in funding for sustainable mobility projects, and has done so for several hydrogen pilot projects in various regions of the Netherlands (see Chapter 4.2.1.2 external markets). Another important example is the ‘motion of Veldhoven’, which aims to provide funding specifically for a transition to zero-emission buses and related infrastructure.

#### 4.2.1.8 Ownership

According to Porter (1998), ownership of resources and infrastructure is varied. Ownership is primarily related to the party responsible for funding, which for a mature hydrogen infrastructure system is likely to be spread over many users, as is the case for the natural gas system today. This section will discuss the current and possible situation regarding ownership. The chapter on possible financing constructions provides more detail on possible pathways.

##### *Ownership types for refuelling stations*

Currently, for refuelling stations and potentially HRSs, four types of ownership status can be distinguished. A refuelling station can either be:

*Company-owned - company-operated (controlled):* These types of stations are often situated along highways and have relatively large fuel capacities. These types of stations are driven at the expense and risk of an oil or gas company.

*Company-owned – dealer operated:* the ownership of the fuelling station belongs to the oil or gas company. The exploitation was handed over to the operator often based on sales-related leases. The traders bear the entrepreneurial risk, and the operating agreement is usually concluded for an indefinite time and is reviewed regularly.

*Dealer-owned – dealer-operated:* This type of station are fully owned by the operator (dealer). The dealer operates on its own account and risk and has a contractual relationship with the oil or gas company on the basis of a fuel supply contract with a legal maturity of 5 years. The contract and clauses however vary greatly.

*Dealer-owned – company-operated:* In this case fuelling stations are owned by a private company (oil or gas company), and operate based on a lease or rental contract and risk

Concerning the possible ownership of the PSA system it is more complicated. When looking at the Steam Methane Reformer currently producing hydrogen on-site, investments were made by the gas company who currently has full ownership. The

same construction is possible for a PSA system, but negotiations would be necessary between TSIJ and the gas company.

In general the ownership is concerned with the party responsible for the investment (see financial incentives section). Therefore, regarding infrastructure the ownership is indeed varied over time, where initial public ownership is expected as the first infrastructures built are believed to be largely publicly funded. One of the main issues regarding public ownership of pipelines for example, is that they will have to be publicly accessible by different users, and influences the quality requirements (Interview Jaap Oldenziel, 2016).

#### 4.2.2 Enterprises

Enterprises consist of both the firms directly related to the supply chain (in-cluster firms) and related and supporting firms that originate outside the cluster. For the hydrogen economy, there is a wide range of actors active in this field, and a categorization can be made with regard to their activities. Although the boundaries can often seem a grey area, a categorization is made with regard to cluster enterprises in Table 28. Not all categories were available in the Netherlands, meaning the results show several gaps. However the main enterprises relevant for this analysis are described.

**Table 28 Enterprise categories proposed by the author**

Enterprise category	Category description
<b>In-cluster firms (directly involved in supply chain)</b>	Hydrogen production, storage, systems, monitoring and delivery
<b>Related and supporting industries</b>	Engineering, integration, application, FCEVs, buses and boats, stationary power units
	Fuel cells, systems, electronics
	Consultancy
	NGOs, network, safety, regulations, codes and standards

##### 4.2.2.1 Related and supplier industries requirements

As mentioned, clusters use goods and necessary services of other enterprises and organisation based in the region. These can include financial services or services such as construction. They can be viewed as collaborators to the cluster, enabling the development and aiding the core cluster group. With regard to hydrogen mobility, these can be engineering companies, application manufacturers and even consultancy companies to draw up strategies.

*Engineering, integration, application, FCEVs, buses and boats, stationary power*

**Table 29 List and description of related and supporting industries in the Netherlands**

<b>Advanced Public transport systems</b>	<b>Development, production, after sales and marketing of high quality public transport system named Phileas</b>	<b>Helmond</b>
<b>ALE (advanced Lightweight Engineering BV)</b>	Design and development of lightweight onboard hydrogen storage tanks	Delft (university)
<b>Alewijnse Marine Technology/Fuel cell solutions</b>	Development, sales, installation and maintenance of fuel cell systems on board inland and sea-going ships, logistic transport auxiliaries and shore power supplies	Nijmegen
<b>BOA Nederland BV</b>	Supplier and manufacturer of flexible piping and system technology, supplies companies such as Nedstack and Hygear	Tilburg
<b>Bredenoord</b>	Specialist in mobile power solutions (fuel cell generators)	Apeldoorn
<b>Brimos</b>	Design and manufacture of a wide range of route information products	Hattem
<b>DutchCell</b>	Standardised packages for small stationary applications	Breda
<b>Fuel Cell Boat BV</b>	Research, development, design, construction, project management, consultancy, marketing and knowledge management of hydrogen fuel cell applications in the marine and inland shipping sector	Weesp
<b>GVB</b>	Public company owned by municipality fo Amsterdam, operates 300 buses in Amsterdam. Formerly owned a hydrogen production and refuelling station	Arnhem
<b>HyEt</b>	Developer and producer of hydrogen decompression systems for fuel cell cars, buses, trucks and generators	Arnhem
<b>Hytruck</b>	Cooperation and partnership aimed to transform a conventional chassis into a FC truck	Beverwijk
<b>NV Nedap</b>	Development of a patented modular bi-directional on- or off grid fuel cell inverter	Groenlo
<b>Prins Autogassystemen</b>	Development of alternative fuel systems mainly for light-duty Otto	Eindhoven

	engines. Hydrogen injectors	
<b>Silent motor Company</b>	Business platform for hydrogen activities	Arnhem
<b>Van Hool</b>	Builds complete range of buses and coaches, and has successfully built hydrogen fuel cell buses, of which five have been supplied to the United States.	IJsselstein
<b>Bam infra</b>	Bam offers engineering consulting, construction, inspection and maintenance for national gas networks. Have experience with both low and high pressure networks.	HQ in Gouda, Various establishment in Noord-Holland, Schiphol

### *Consultancy*

There are several consultancy companies active in the field of hydrogen with various expertises. These organisations could complement a hydrogen cluster by focusing on legal barriers and project management. Consultancy company Sweco is currently in charge of project management of the development of hydrogen mobility using by-product hydrogen, however TSIJ organises the monthly meetings on the topic. Other possibilities for consultancy companies are Altran (Schiphol-Oost) and Royal Haskoning DHV, which is situated in Zaandam.

**Table 30 List of relevant consultancy companies in the Netherlands**

<b>Altran</b>	Sustainability department and hydrogen department specializing in system design, safety, project management, feasibility studies, audits, interim management and consultancy relating to renewable energy and hydrogen	Schiphol-Oost
<b>REBEL</b>	Advises, invests and realises in various industries such as energy, infrastructure and mobility	Rotterdam
<b>Cogen Projects</b>	Independent energy consultancy company, project support, technology and market studies, core activities around sustainable energy technologies, implementation of new technologies such as fuel cells	Driebergen-Rijsenburg
<b>Royal Haskoning DHV</b>	Engineering, design and project management consultancy firm, active in energy and infrastructure sectors	Zaandam, Amsterdam
<b>Ecofys</b>	Leading consultancy focusing on hydrogen and fuel cells. Techno-	Utrecht

	economic feasibility studies, policy analysis, strategy/scenarios and expertise in various hydrogen and reformer-based application, including transport, stationary and industrial and large CHP applications	
<b>Gasunie Engineering &amp; Technology (GET)</b>	Research, development, innovation, analysis, measurement, testing, calibration, studies, audits, engineering, consultancy, and training with regard to the transport and use of natural gas and gaseous energy carriers.	Groningen
<b>SWECO</b>	An international engineering consultancy firm that specializes in mobility and infrastructure, energy and industry. Currently responsible for project management of hydrogen from TSIJ and mobility in province of Noord-Holland	Alkmaar

#### 4.2.2.2 Firm strategy, structure and rivalry – firms directly in supply chain

Included in this section are in-cluster firms directly in the supply chain of hydrogen distribution. These companies have expertise or can potentially contribute to the production of hydrogen, storage, systems, monitoring and the delivery of hydrogen. These companies can be part of the core of a potential cluster. As stated in the H2 mobility in Germany, the consortium structure is primarily industry-led, meaning the proposed research programs match the expectations and needs of industry (FCH, 2016).

##### 4.2.2.2a Hydrogen suppliers



As presented in the problem statement, **Tata Steel IJmuiden** can act as the hub of a potential cluster and the source of hydrogen for the region. The company has the potential of supplying over 35,000 tonnes annually. The company is under pressure to reduce emissions and increase energy efficiency, and is exploring possibilities of by-product hydrogen distribution. The core business is steel production and distribution, and requires collaboration in order to realise possible distribution.

##### 4.2.2.2b Infrastructure suppliers and gas companies



**DeMaCo** is situated within the region of Noord-Holland, and specializes in cryogenic infrastructure for various partner industrial gas companies, research institutes and contractors worldwide. This technique is used for gas in extreme low temperatures (fluid), and in this field the company advises, designs, develops, produces, tests and installs relevant customer specific infrastructure. They operate in a wide variety of industries such as pharmaceutical, automotive and aerospace with corresponding gases such as liquid

nitrogen, helium and LNG and hydrogen. Their main products are cryogenic transfer lines, valves, storage tanks, Liquefaction equipment and liquid hydrogen applications. They operate in hydrogen networks such as the Dutch Hydrogen and Fuel Cell Association, and have participated in hydrogen piping and storage projects internationally.



**Royal Dutch Shell** has a division focused on developing the fuel cell and hydrogen industry and provides filling stations in key locations. They are mainly experienced in hydrogen refuelling services in the field of hydrogen. They have experience with collaborating with vehicle manufacturers, and are operating in various networks such as the Fuel Cell & Hydrogen Joint undertaking and the Dutch Hydrogen and Fuel Cell Foundation. Shell is part of the H2Mobility project in Germany with joint venture partners Air Liquide, Daimler, Linde, OMV and Total. The aim is to add the new hydrogen infrastructure to existing fuel retail sites.



**Air Liquide** has over 40 years of experience with managing the entire hydrogen chain. This includes the production of hydrogen, distribution, storage and even various fuel cell applications. Alongside this, Air Liquide Group is a contributor to a wide variety of international projects. They currently operate two fully operational hydrogen refuelling stations in the Netherlands with a third one under construction (Jaap Oldenziel, 2016). The company also has experience with by-product hydrogen separation, which at the time was not an economically viable project (Jaap Oldenziel, 2016).



**Air Products Nederland B.V.** is a supplier of industrial gases and various other products. The company has an extensive hydrogen portfolio, which includes gaseous and liquid hydrogen, storage and transport systems, small- and large-scale production plants and engineering consultancy. Furthermore, the company delivers fuelling stations for the automotive market, and contributes to various international commercial and demonstration projects related to hydrogen. Similar to Shell and Air Liquide, the company is part of various networks such as the Dutch Hydrogen and Fuel Cell Association. The company is part of a global organisation Air Products & Chemicals Inc.



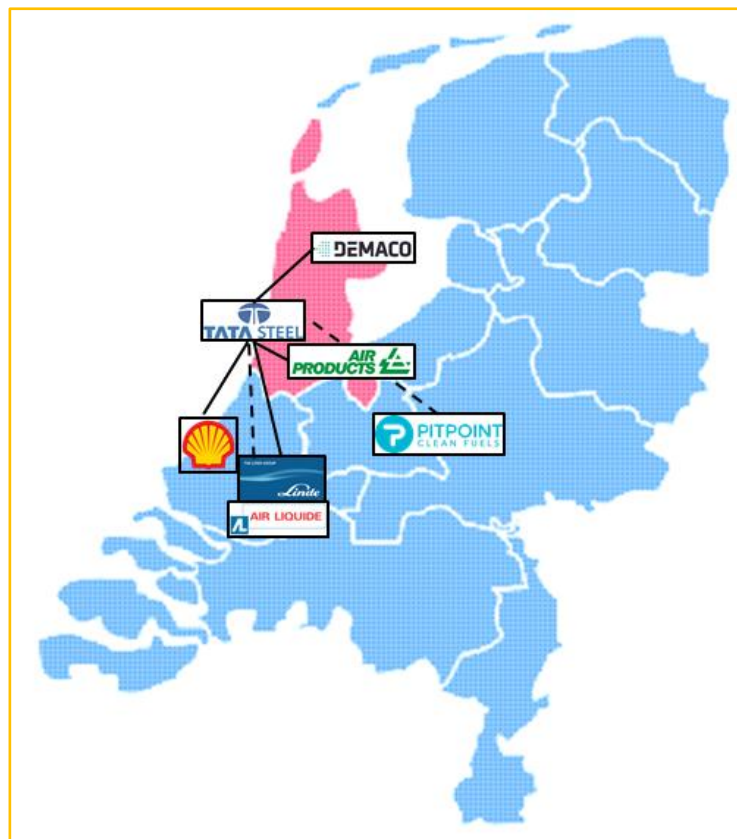
**Linde Gas Benelux** is the worldwide market leader of hydrogen production units for various applications in the chemical, petrochemical and metallic industries. Similar to Air Liquide, they provide the entire hydrogen infrastructure for gaseous and liquid hydrogen. This includes hydrogen production units (steam methane reforming), electrolysis and partial oxidation, 'over the fence' supply via pipeline and trucks and trans-shipment, filling stations, storage and consultancy services. Furthermore, they are engaged in cooperation with science and research

institutions, and closely cooperate with the automotive industry to develop necessary innovations. Interesting networks are the Deutsche Wasserstof Verbund, the National Hydrogen Platform and the JTI. Furthermore, the company currently operates a Steam Methane Reformer at Tata Steel IJmuiden of approximately 1000 kg/day, of which currently half is used, resulting in an surplus capacity of 500 kg/day.



**Pitpoint** is relatively new company aimed at the creation of a clean fuel infrastructure. Their products are CNG (compressed natural gas), LNG (liquid natural gas), hydrogen and electric mobility. The company aims to realize a hydrogen infrastructure, and focus on the entire supply chain from the source to the retail station (Pitpoint Meeting, 2016). They are able to aid in the design, construction, financing, maintenance and operation of a refuelling station. Furthermore, they have experience with permitting, feasibility and risk-, financial-, environmental and technical reliability analyses (Pitpoint Meeting, 2016). They currently operate a hydrogen refuelling station in Helmond, and have acquired subsidy for a hydrogen station in Arnhem in a collaboration with the Ministry of Infrastructure and Environment, the Province of Gelderland, the municipality of Arnhem and public transport company Connexion (). Furthermore, the company is active in several international networks active in standard setting and research on hydrogen as a fuel (Pitpoint Meeting, 2016)

The potential linkages of the suppliers and their geographical location are shown in Figure 25 Most of the companies are based outside of the region of Noord Holland, where the cluster hub is based. From discussions and in relation to the province of Noord-Holland, it becomes apparent that an initial cluster is absent in various ways. For one, a clear vision and designation for the are regarding infrastructure build-up is non-existent, as are the potential advantages related to the use of complementarities. Joint-marketing is not being deployed, joint-bidding for prospective HRS locations is neither being discussed nor is it being done. From attending the



**Figure 25 Potential linkages of in-cluster firms constructed by the author**

National Hydrogen Platform meetings, personal relationships and trust are slowly being established, but there are many gaps to be filled. As is shown in the previous chapter, creating industrial symbiotic linkages requires a successful network build up, to which establishing a successful clustering is related and is in some way an extended version of IS. Therefore, these companies currently do not meet the requirements for establishing a successful cluster. The opportunities are however present, which is further explored in the following section.

#### 4.2.2.2c Quality of buyer-supplier relationships

Regarding the quality of buyer-supplier relationships, it can best be described according to the National Hydrogen Platform. In general, all parties are open to new ideas, as they all benefit from a developing hydrogen market. However, openness to the use of by-product hydrogen that originates from coal seems to differ per company.

One company explained that currently in the Netherlands enough carbon free hydrogen is produced to fuel over 3 million FCEVs already. Electrolysers are coupled to the grid and produce hydrogen to the companies network. This happens through electrolysis of hydrochloric acids, and when the provided electricity for this process would be from renewable energy sources, the hydrogen would be green and sustainable. An important eye-opener regarding the hydrogen economy is that could potentially be sufficient amounts of green hydrogen based on current available electrolysers, just not enough green electricity (from renewable energy sources) as input. This hydrogen however meets the requirements for green certification (carbon free definition) and is abundant, making it difficult for by-product hydrogen to compete as it is not carbon free and may not meet the certification demands. Furthermore, should this company participate in the provision of by-product hydrogen from coke oven gas, it could have a negative impact of their image, as they are striving to provide green certified hydrogen. Furthermore, as the company already produces hydrogen efficiently, the chances are that the cost of their hydrogen from outside the region will be lower. As the company already owns the tube trailers, the extra transport costs would be marginal. Such a company does however have broad experience with producing hydrogen from various gases, and is open to assess possibilities especially due to the high hydrogen content. However, the main question then would be a matter of competition: the profitability would be assessed of the hydrogen from coke oven gas which is currently not Green Certified, and compared to that of current processes such as electrolysis which are green certified (Interview Jaap Oldenziel, 2016).

During the research a meeting was made with another company that specialises in hydrogen infrastructure. This organisation stated that what they see is some parties say that in order to build a HRS the hydrogen source should be from electrolysis and 100% green. This companies vision differed, and stated that in order to build up an infrastructure the initial sources do not have to meet the demand of being 100%, which is only possible in the future when renewable energy start having excess

capacities. At the moment this firm was just looking for sources of hydrogen (Interview Erik Büthker, 2016).

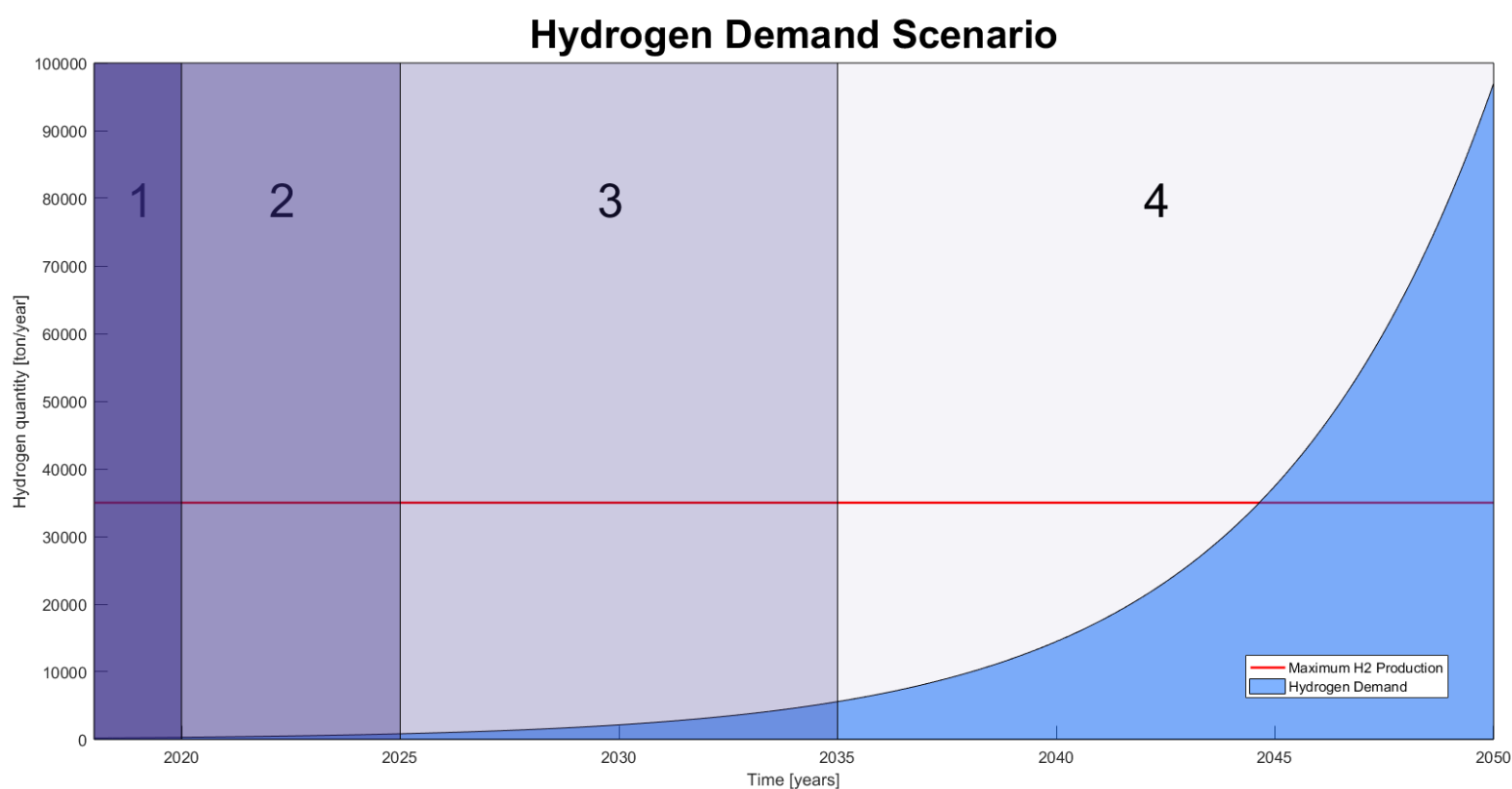
A third large player in the oil and gas industry came with a similar statement. Their interest was on current regionally present hydrogen sources and not necessarily over concerned with the sustainability of the source (Interview Alice Elliot, 2016).

### 4.2.3 Market scenario for Noord-Holland

In line with the envisioned development of the hydrogen mobility market stated in the previous chapters, the following scenario of market development for Noord-Holland is presented by the author. The development consists of four stages, and is mostly concerned with the type number of applications per phase and the number refuelling stations. These phases and the related fleet size and corresponding hydrogen refuelling stations for the Netherlands are shown in table 31 and are translated to the province of Noord-Holland. As the this indication of fleet size is quite generic and encompasses all types of future vehicles, the choice for the total future fleet size for Noord-Holland specifically was approximated as stated above instead of simply 15% of the total fleet size in the Netherlands.

**Table 31** Indication of fleet size and HRS amount in Noord-Holland per market phase

Market development phase	Indication of fleet size NL total	Indication amount of HRS NL total	Amount HRS NH (15% NL)	Indication fleet size NH (15% NL)
<b>1) Market preparation</b> <i>2016-2020</i>	<100	5-20	1-3	<15
<b>2) Early market introduction</b> <i>2020-2025</i>	500-5000	20-50	3-8	75-750
<b>3) Market commercialisation</b> <i>2025-2035</i>	100,000-200,000	50-200	8-30	15,000-30,000
<b>4) Mass market</b> <i>&gt;2035</i>	40% market share – 5,000,000	1000-1500 (4000 stations total, 40%)	150-225	500,000



**Figure 26** Market scenario for Noord Holland presented by the author

The different market phases are shown in Figure 26 and the corresponding possible growth scenario of the hydrogen demand for the province of Noord-Holland is shown. According to this scenario, the hydrogen from Tata Steel IJmuiden is sufficient to provide hydrogen fuel for mobility during at least the first three phases of market development in Noord-Holland. Furthermore, industrial symbiosis of hydrogen can provide a large portion of the mass market uptake phase, up to 2045. After this stage alternative sources will be needed, and within the presented perspective of a transitional and future system, these alternative sources of hydrogen will stem from renewable production processes. Each market phase will now be explained in more detail taking into account the various findings throughout this research.

### (a) Market preparation between 2016 – 2020

During the market preparation phase, captive fleet vehicles can play an important role. This can be explained primarily through the investment risk associated with the development of refuelling stations. Without the development of a network of hydrogen refuelling stations, the roll-out of hydrogen applications are not likely to rise from a market standpoint. As mentioned in the section on hydrogen costs, during the first decade the delivery costs are dominated by retail costs due to low utilization of hydrogen refuelling stations (Ball & Weeda, 2015). The main investment risks associated with development of refuelling stations are related to the high capital and operational costs, and the under-utilization of the station itself (IEA Roadmap). This leads to a negative cumulative cash flow over 10 to 15 years as shown in Figure 10.

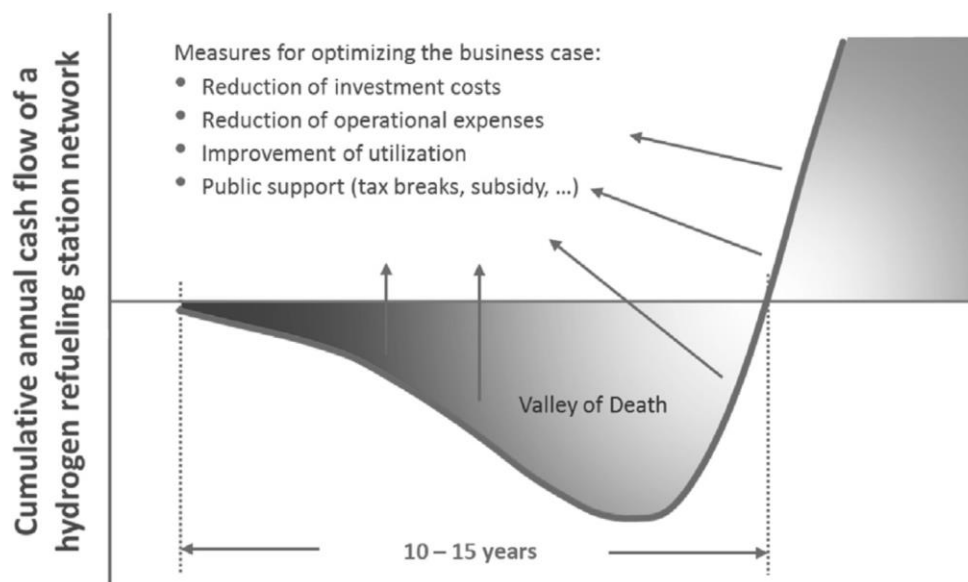


Figure 27 cumulative annual cash flow of a hydrogen refuelling station, 'valley of death' (source: Ball & Weeda, 2015)

The figure has been dubbed as the “valley of death” in terms of cash flow related to the underutilisation of hydrogen refuelling stations. Authors present several measures to optimize the business case, of which one is a key measure when defining the most interesting market during early stages of development – maximizing asset utilization.

Ball & Weeda (2015) argue that fleet vehicles such as buses and delivery vans largely operate locally and run on short, regular routes while returning to a central depot for refuelling and maintenance. This makes captive fleets ideal candidates for establishing hydrogen infrastructure during the early phases of implementation as there is no need for an extensive network of stations at which the fleets refuel. A base location for refuelling provides the conditions for associated costs to be kept at a minimum, as the high utilization and higher annual mileage contribute to an earlier economic viability of fleet vehicles than personally owned commercial vehicles (IEA, 2015). Another argument for fleet vehicles compared to personal vehicles are the possible concerns about passenger safety in various situations related to hydrogen mobility (in tunnels or enclosed parking spaces) (Ball & Weeda, 2015).

During this market preparation phase, potential markets include, personal vehicles, urban and rural public buses and possibly delivery vans that operate in captive fleets. Ownership of these fleets is either the (local) government and companies actively pursuing green practices. Together, the total fleet will consist of under 15 FCEVs and Fuel Cell Electric buses which will be implemented alongside the current Battery Electric buses currently operational. The refuelling station infrastructure will start with 1 and upgrade to 3 hydrogen refuelling stations. As shown in Table 17, the National Hydrogen Platform aims to realize at least two refuelling stations in the province of Noord-Holland during market preparation (until 2020). These stations are aimed to be on so-called A-locations, meaning close to highways in order to develop initial network coverage. These locations coincide with the main corridors presented by the TEN-T corridors show in Figure 7 in the section on external markets. The locations for these are Amsterdam Schiphol and along the highway A1 Amsterdam (presentation Fred Hagendoorn, 2016). An initial coalition is formed by a “coalition of the willing”, which can be infrastructure companies Shell, Pitpoint and Air Liquide. Tata Steel IJmuiden and Linde Gas are especially part of the initial consortium, as they provide the initial source of hydrogen from the on-site steam methane reformer. A coordination body likely to be a consultancy company who has specific expertise in infrastructure and government negotiations helps to govern the initial steps of forming the collaboration and network building. The consortium can opt for public funding aid from the Ministry of Infrastructure and Environment or the Fuel Cell and Hydrogen Joint Undertaking from the European Union. Via meetings and attending Assemblies at the National Hydrogen Platform institutional capacity is increased. The consortium will personally invite delegates from the province to join meetings and aim for a public-private partnership or Green Deal for refuelling station roll-out. This aids in overcoming public hurdles such as location permits.

## **(2) Early market introduction between 2020 – 2025**

During this phase, the captive fleets of personal vehicles, delivery vans will be extended to a wider set of user. As of 2025, 50% of public bus transport should be zero-emission drivetrains (see policy chapter 4.2.2.1b), which means the public transport companies will further implement FCE buses mainly in rural areas where

bus distances are longer and speeds are higher than buses in cities. Alongside captive fleets, specialty vehicles are added in this market phase such as forklifts and street sweeping trucks, this last application owned by the province of Noord-Holland. The number of hydrogen refuelling stations is upgraded to 8 in total in rural and urban areas as well as Schiphol airport. The locations for refuelling stations will be strategically chosen to expand the initial network of the highway A1 and Schiphol, taking notice of the main TEN-T corridors. As the hydrogen infrastructure is starting to take form in the province as well as on a national level, international car manufacturers gain confidence in choosing the Netherlands as a launching customer for their personal fuel cell electric vehicles. This results in the uptake of 'innovators' and 'early adopters' of personally owned vehicles, and also companies with sustainable ambitions using freight trucks and delivery vans will start adopting FCEVs. Public buses, captive fleets such as taxi's and delivery vans are expanded. The existing refuelling stations can now be categorized as pseudo-sustainable, meaning they have entered the transition phase of bankability. In this stage, the consortium attracts public banks for infrastructure funding.

### **(3) Market commercialisation between 2025 – 2035**

As of 2025, the hydrogen mobility market will enter in the phase of commercialisation. This means many of the existing fuelling stations can operate without further government or public bank financial aid. As stated in chapter 4.2.1.2 on external markets, a pre-condition is the development of a national and international market. According to projections, neighbouring country Germany will have expanded its infrastructure to 400 refuelling stations before the beginning of this phase (approximately 2023). This means the neighbouring hydrogen mobility market and infrastructure has now seriously developed, which is directly linked to the A1 highway leading to Noord-Holland. In this phase personal FCEVs, delivery vans and other applications named in the previous sections expand and diversify to between 15,000 to 30,000 vehicles in Noord-Holland. This phase is characterised by the uptake of hydrogen applications by the 'early majority' or 'early adapters'. During this phase, the amount of fuelling stations will have to be increased to approximately 30 stations. Half of the public bus transportation is now zero-emission, and the amount of fuel cell electric buses will be increased by companies Connexxion and GVB. Also, Schiphol airport has now expanded its fuelling stations, and most ground power units are now electrified and run on hydrogen.

### **(4) Mass market from 2035 onwards**

Backed by the policy targets, all newly-sold vehicles have to be zero-emission as of 2035 onwards, resulting in a phase where the mass market will start to develop. As shown in Figure 26, the hydrogen demand increases exponentially. All FCEVs will have a diverse portfolio of vehicles, and long distance travel and distribution is possible due to external market infrastructure. As market demand will increase exponentially up to 500,000 FCEVs during this phase, the amount of hydrogen

refuelling stations to provide this market will grow correspondingly, increasing to 150 and up to 225 stations. All capacity types of refuelling stations are now operational, ranging from stations to large station able to provide 1000 kg of hydrogen on a daily basis. The consortium continues to expand and improve its infrastructure, ultimately providing 40% of the entire mobility system in Noord Holland with hydrogen.

### 4.3 What are the implications for Tata Steel IJmuiden in the region of Noord-Holland?

For the sake of readability and clarity, this section has reduced to implications for implications concerning technology, economics and governments. First and somewhat related to the theory of back-casting, attention is paid to the future implications building on the findings of the previous findings and results. Subsequently, the implications for the company regarding the current situation are defined, and the barriers to overcome on the short term. As a result it is possible to uncover what important gaps between the current and future situation are present, which are added to the current situation description.

#### 4.3.1 What are the implications for a hydrogen cluster in the future?

Regarding **technology**, ideally the hydrogen mobility has reached a level where most of the hydrogen Tata Steel IJmuiden is able to provide is utilized, approximately 35.000 tonnes per year, which according to the scenario would be around the year 2045. During this period, other sources of hydrogen, preferably from electrolysis with renewable energy sources from the offshore wind park established on the coast of IJmuiden complement the by-product source. A wide variety of applications are on the road such as buses, personal vehicles, trucks, taxi's and other light duty vehicles and heavy duty vehicles. Sufficient hydrogen refuelling stations are in place to meet demand in urban and rural areas and at Schiphol airport. The standards for refuelling stations, infrastructure and hydrogen applications have been developed and set by agencies and industries. Furthermore, a pipeline network has been realized to replace the use of compressed gas trucks, as this is the most economical distribution pathway. Innovation regarding key technologies have created efficiency and cost competitiveness throughout the entire supply chain.

The **economics** surrounding the cluster are now increasingly favourable. Due to innovations and economics of scale, investment needs have dropped to a point of sufficient returns and the right balance between capital expenditure and operational expenditure. The hydrogen infrastructure has therefore reached a bankable and commercial phase, and the cluster is now able to pay off subsidies, public and possibly commercial bank loans. The contribution of hydrogen refuelling stations to the hydrogen price is now minimized, meaning the sales price of hydrogen at the nozzle is under €5 per kg and competitive with gasoline and diesel. Due to scale economies at the source at Tata Steel IJmuiden, the production costs of hydrogen have dropped to a bit over €2 per kg. On the application side, fuel cell electric vehicles have dropped in price due to scale economies and technological innovations, making them competitive to competing drivetrains such as battery electric vehicles and gasoline cars.

As for the **governance**, an ideal institutional infrastructure has been realised. Cluster firms and related organisations, knowledge institutions and governments use the latest insights on clustering development. Between all stakeholders, high level of

social interaction and mental proximity are present and communication is open, leading to knowledge spill-overs. This has led to strong horizontal inter-firm networks where organisations have access to employees, suppliers and specialized information from inside the cluster. Coordination bodies are in place to govern the cluster, and monitor training and educational programs to keep them up to date. The cluster organisations make use of complementarities such as joint-marketing and joint-bidding while mutually managing the infrastructures. Overall, the cluster has a clear vision and designation.

#### 4.3.2 What are the implications to realize a hydrogen cluster now?

For an industrial symbiotic cluster for by-product hydrogen, the geographical location of Tata Steel IJmuiden is favourable. It is proximate to highways such as A1 highway, which is connected to the corridor grid presented by European trans-national Transport Network Program. Furthermore, proximate markets such as high density urban areas Haarlem, Amsterdam and especially Schiphol airport. Schiphol has expressed interest in hydrogen, and according to the projections of the National Hydrogen Platform a HRS should be established before 2020. Furthermore, a long term perspective shows that in order for by-product hydrogen to be replaced by green hydrogen from renewable energy, the geographic location is also favourable as plans for offshore wind on the coast of IJmuiden are being developed.

#### Technology

As a source for hydrogen in the province of Noord-Holland, Tata Steel IJmuiden is able to generate several pathways. Based on the scenario for market demand in the region, it is apparent that the existing steam methane reformer is able to provide sufficient hydrogen for the first two market phases (preparation and early introduction). In these phases, the demand (<150 tonnes) is expected to remain below the amount of excess capacity of the Steam Methane Reformer. However, this hydrogen does not yet meet the required purity standards, so investments in purification technology will be necessary. The cluster may also decide to invest in a PSA installation immediately. This installation would however have to be tailor-made and tested as it has been mathematically modelled, and requires large amounts of investments. There are however current examples of companies of PSA systems separating hydrogen from flue gases including the Tata Steel plant in Jamshedpur in India, which could be contacted for advice. Gas company Air Liquide has expressed its capability of delivering such technology.

Hydrogen refuelling stations are available in different capacities and several companies currently offer the technology. Standards are increasingly being clearly defined, 350 bar for forklifts, buses and range-extender type road vehicles and 700 bar for full power FCEVs such as personal vehicles. The investment costs differ per HRS capacity, but so does the hydrogen price – this is projected to be lower with increasing capacity. With an initial low demand the HRSs have the risk of being underutilized and therefore should be scalable, which is not always the case. In order

to decrease the risk of underutilization, HRS investors should initially concentrate on captive fleets of buses, personal vehicles and possibly delivery vans owned by government and companies actively pursuing green practices.

## **Economics**

It is apparent that initial initiatives of hydrogen infrastructure and refuelling stations require large amounts of public support and financial incentives to overcome the high investment challenges. Investment costs for pressure swing adsorption technology, infrastructure and hydrogen refuelling stations are currently high, as are the risks related to underutilization of the technology. Companies are not ready to invest at a large scale, and pilot projects in order to get acquainted with the new technology are necessary and being deployed. Costs of applications such as fuel cell electric vehicles are currently still high and non-competitive with gasoline counterparts. This makes risks for automotive dealers, public transport companies and governments to invest in such technologies high, especially as the related infrastructure is not available (chicken and egg dilemma).

For the hydrogen source, during the initial phases of market development could be relatively low as investments in purification technology are required instead of an entire PSA installation. Investing in an entire PSA installation would require a minimum of €19 million, for which TSIJ is not likely to provide funding as it is not their core business. With regard to infrastructure, several gas companies have compressed gas trucks available, potentially decreasing cost necessities. Investment in HRSs is currently however extremely risky, as the market is non-existent and investment costs are high.

## **Governance**

With regard to governance, there are many requirements not met for a successful cluster. The national hydrogen platform is developing plans to which many interesting stakeholders contribute and take part in meetings and assemblies. This provides an interesting basis to establish personal and trust relationships between potential cluster partners. However, knowledge sharing and relationships are currently in very early stages, only several meetings have taken place. Interest in by-product hydrogen is however rising, as during the course of this research several parties have contacted Tata Steel IJmuiden. It is critical that gas companies and Tata Steel IJmuiden start sharing information resulting in knowledge spill-overs and increase of social interaction. Open communication between the various organisations will be crucial, ultimately leading to horizontal inter-firm networks. A coordination body such as a consultancy or in-firm body could be relevant to manage and strengthen these linkages. The following advice can be given to coordination bodies, derived from Roberts (2004):

- Promote opportunities to establish genuine partnerships and engagement with communities and government in developing a more responsive attitude towards sustainable practices.
- Locate industries strategically to optimize the flow and capture of by-products and wastes
- Co-locate industries that will benefit economically from the exchange
- Provide a catalyst to create synergies and an environment for fostering technical production in a cleaner way
- Provide an appropriate 'Smart infrastructure' to insure the growth and to maintain high level of innovation as the basis of their competitive advantage
- Support industry policies and incentives to encourage innovation, collaboration and commercialization of new improved product developments regarding by-product hydrogen
- Demonstrate commitment to the benefit of industries that have strong, sustainable development.

Once these networks are characterised by strong linkages, the initial cluster of TSIJ and industrial firms should develop a clear designation of the cluster with regard to establishing the initial market. The cluster can make use of complementarities such as joint-market of hydrogen projects and start joint-bidding on specific locations.

The province of Noord-Holland who plays an important role has however withdrawn its interest, and is currently more interested in battery electric vehicles. It is obvious that for a hydrogen cluster the ownership related to various aspects such as hydrogen refuelling stations, infrastructure and even technology to provide a source of hydrogen is unclear who would invest and take ownership.

## Conclusions & Discussion

This research has focused on by-product hydrogen from Coke Oven Gas at Tata Steel IJmuiden as a potential source for a hydrogen mobility in the province of Noord-Holland. Tata Steel is exploring options to enter the hydrogen market, and as hydrogen mobility is currently gaining interest internationally and viewed as one of two zero-emission mobility solutions, this has been the main focus. However, hydrogen mobility in the Netherlands is currently in its infancy and close to non-existent, making the analysis a complex process. The hydrogen content is a waste gas stream and not part of Tata Steel's core business. The company could build the necessary infrastructure up to their fence, but distributing it 'beyond the fence' requires more information, as a novel regional source does not automatically lead to market development. Therefore—research was needed on the requirements for hydrogen mobility regarding required technology, policy instruments, institutional infrastructures and economic feasibility. Subsequently, a broad scope was unavoidable to define the set of requirements related to the topic.

Overall, the model proved useful to create an overview of requirements related to by-product hydrogen in the steel industry. The cluster framework allowed for a regional perspective, allowing to take other sources of hydrogen into account. An important remark is the eventual framework assumed a static nature, whereas clusters are dynamic and subject to change over time. Therefore, the choice for a minimum set of requirements was made with a slight adaption concerning the market section. This and the main findings for the sub-questions will now be explained.

*Q1: How can theories from various academic fields related to Industrial Symbiosis be integrated in the cluster concept to reach an ideal model of requirements and indicators?*

As the hydrogen source is a by-product, the first step was to uncover relevant scientific approaches related to by-product utilization. This led to the notion of Industrial Symbiosis, a field concerned with revalorization of various by-products and the process of exchanging them between separate business entities. Models of Industrial symbiosis are predominantly case specific and have many embodiments such as eco-industrial parks, and the field has an internal debate whether practical development can arise from a grand plan or should be subject to self-organisation.

Nonetheless, an extensive literature review resulted in valuable input to formulate an initial set of requirements, and in a later stage an international study on success-factors for eco-innovation (which incorporates industrial symbiosis) was used for extension.

However suitable, Industrial symbiosis proved to be insufficient to cover the broad scope of this research. In order to assess the requirements for distributing by-product hydrogen beyond the fence and the development of a competitive market, an additional framework was needed. As modern competition depends on productivity and productivity growth and not on individual enterprises, it was found that the formation of an industrial cluster is an important pre-requisite. Clusters were found to be particularly relevant, as according to Gibbs (2003), development of Industrial symbiosis and eco-industrial parks are intrinsically heavily reliant on the construction of local and regional networks, also known as clusters. Based on statistical evidence for economic development, Michael Porter presents the manifestation of a cluster at work as the 'diamond' framework, with four interrelated facets important to local competition. As competitive advantage is naturally a requirement for a commercial market to develop, these four facets could be regarded as such. The facets proved useful, as they encompass a broad scope of regional conditions, demand conditions and the assessment of firms both in and outside of a potential cluster. Some facets were however broadly stated and more of metaphoric and figurative nature, complicating the translation to usable requirements or indicators. Again, additional insights on clusters were imperative.

This led to the GEM model by Padmore & Gibson, designed for operational use at the regional level and allowing systematic assessment of a cluster. While comparing the two models, it was obvious this was an extension of the diamond framework and hence named GEM, an acronym to diamond. Merging the two models provided a solid foundation for assessment.

The final step for the development of a comprehensive model was combining the insights from industrial symbiosis and clusters. During a step-by-step comparison, many similarities were found, and indicators from industrial symbiosis complemented those found in clusters, and placing them under the formulated requirements proved a good fit.

*Q2: How can the developed model be applied to the case study of Tata Steel, hydrogen mobility and the province of Noord-Holland in order to determine the minimum cluster requirements?*

In order to specify minimum cluster requirements, the formulated industrial symbiosis cluster model was applied to the case study of Tata Steel IJmuiden and the province of Noord-Holland. During the course of research, a temporal aspect was added in relation to the market demand requirements. This made a simplified positive scenario possible for market development, which was necessary and influenced several aspects of the cluster not initially integrated in the model. As the starting point is Tata

Steel IJmuiden exploring the possibilities to supply hydrogen, the scenario is a combination between market projections for hydrogen mobility and Tata Steel as main supplier, building on the assumption that the company distributes the total amount available. For this reason, other possible sources were excluded from the scope.

### **Requirement of external markets**

First of all, realising the development of a hydrogen and fuel cell market in Noord-Holland is highly unlikely when external markets to the region and the nation in parallel do not. Globally, hydrogen mobility is in its infancy, however there is a wide scale of initiatives. On an international level, Denmark, Germany, the US (California) and Japan are the frontrunners in establishing a hydrogen refuelling infrastructure. Important initiatives by the European Union are the Fuel Cell and Hydrogen Joint Undertaking (FCH JU) and the Trans-national Transport Network Program (TEN-T), the latter encompassing joint forces between Denmark, France, Sweden and the Netherlands. TEN-T has established several filling stations, of which one in the Netherlands, H2 Mobility in Germany aims to establish 400 stations by 2023, and France and the UK have developed H2 Mobility projects of their own. The Netherlands is working on an H2 Mobility program, and currently houses two operational hydrogen filling stations outside Noord-Holland, with three more planned by 2017.

### **Requirements of local market**

Currently there is no hydrogen mobility in Noord-Holland. A simplified scenario was therefore proposed as a guideline for other requirements and a gross estimate of potential hydrogen demand. Based on this, the hydrogen demand is likely to remain low during market preparation (3 tonnes/year, 2020), grow from 150 to 6000 tonnes/year during the introduction and commercialisation phases (up to 2035) and finally exceed an annual 100.000 tonnes by 2050. Gradually fleet types will diversify, while initially captive fleets are required in order to minimize risks of underutilization of hydrogen refuelling stations.

### **Technology requirements**

Fuel cell technology in mobility applications require high purity hydrogen (>99.99%). Initially, the focus was solely focused on by-product hydrogen from COG, for which two pathways were considered (2 PJ, 5000 tonnes/year) and the total 14 PJ (35,000 tonnes/year). Separation requires pressure swing adsorption, adsorbents, compressors and storage units, which are considered proven technology. During the research, an additional operational Steam methane reformer was found with an excess capacity of 160 tonnes/year, but it would require additional purification technology.

For 'beyond the fence' distribution, two main pathways are considered, namely compressed gas truck transport and pipeline transmission. For distribution under 5000 tonnes/year and between 50 and 150 km, compressed gas trucks are economically the preferable option, should supply further increase, a switch to pipeline transmission is favourable. Two main standards for hydrogen refuelling stations, 350 bar stations for heavy duty vehicles and 700 bar for light duty vehicles, the latter ranging from small to large capacities up to 1000kg/day. During initial stages of market development, hydrogen refuelling stations are required to be scalable to growing demand.

### **Economic requirements**

The required investments for a PSA system up to the point of storage depend on the scale of hydrogen separation. For the 2 PJ pathway of 5000 tonnes/year, total investments up to €19 million would be required, for separation and storage of the entire stream of 35.000 tonnes/year investments would exceed €60 million. Cost projections related to other sources of hydrogen are expected to remain relatively steady and estimated between €3-4/kg, and can be seen as a cost benchmark. Scale benefits in relation to the two pathways show a price drop in the hydrogen delivered at the fence from €3- €2/kg, making by-product hydrogen economically competitive. Cost addition for distribution are estimated at €1/kg. Hydrogen refuelling stations vary in capital expenditure based on capacity, ranging from €0.8-2.2 million. Similar to the PSA system, scale benefits are applicable as the daily demand increases.

Financial incentives are required during initial stages of infrastructure and HRS roll-out and decrease over time when demand increases. The main potential investors include strategic investors (industry stakeholders), private sector financiers or public and development banks. Project finance through leverage with loans is considered the preferable option for the early stage. Several public European funds are available for hydrogen mobility (Fuel Cell & Hydrogen Joint Undertaking, European trans-national Transport Network Program), however the process of acquisition is complicated. On a national level, funding and subsidies for the western part of the country for carbon free economy are also possible, and the Ministry of infrastructure and environment has participated in the funding of several pilot projects around the country.

### **Governance requirements**

In order for a regional cluster to prosper, a strong institutional layer is imperative. The province has the ability to aid business in provision of infrastructure, knowledge and innovation and education. Provincial delegates should actively participate in platform initiatives where knowledge is diffused regarding hydrogen mobility (National Hydrogen Platform). Furthermore, the government may act as a coordination body of a cluster, however this role can also be filled by other third-parties such as consultancies. Quality relationships and trust are important to decrease the amount of mental proximity. A platform is a good starting point to establish initial links, and

regular meetings to strengthen these. A clear shared objective and vision is also important. In clusters firms should make use of complementarities such as joint-marketing, joint-bidding and scale benefits, and be granted access to specialized information. With regard to the infrastructure, ownership will develop, and is likely to belong to public financiers during initial stages, and switch as commercial feasibility increases.

*Q3: What recommendations can be made for Tata Steel for the current and future situation?*

One of the main conclusions is the cluster development is currently close to absent regarding hydrogen mobility in the province of Noord-Holland. However, there is potential for which recommendations can be made. Overall Tata Steel is strategically located, as it is close to dense urban areas, Schiphol airport, main highways such as the A1 (A-location). Especially Schiphol is an interesting market, as it is geographically a small area which is favourable for distribution. Furthermore, in the event of a future switch to green hydrogen from renewable energy and electrolysis, the location makes a strong case as wind parks are planned off the coast of the company with neighbouring landing points for electricity cables. In order to provide recommendations, division between the current and future situations are based on the two potential pathways of hydrogen distribution at Tata Steel IJmuiden.

#### Current situation

##### **Technology**

In order to prevent initial large-scale investment, the excess capacity of the existing Steam Methane Reformer could be utilized as an initial source. Modification of the existent system is however necessary, as the hydrogen does not meet purity specifications for FCEVs. This excess capacity seems sufficient for at least a market preparation phase and likely for an introduction phase of hydrogen mobility. During this time, hydrogen flow and distribution distances are low, making compressed gas trucks the preferable option.

##### **Governance**

In order to distribute hydrogen beyond the fence, cluster formation will be necessary. As ownership of the current Steam methane reformer does not belong to Tata, discussions and negotiations will be necessary with the gas company. This gas company shall have to be included in further cluster developments. The national hydrogen platform provides a solid basis to start building trust relationships with potential infrastructure companies, and create awareness of all potential hydrogen sources. Participating in meetings of the infrastructure and mobility market development task group within the platform can provide up-to-date developments in the field, and the option to discuss the role of by-product hydrogen. Several meetings

were established during this research with infrastructure companies, to introduce the topic of by-product hydrogen at Tata Steel. The companies have the technical expertise and resources to establish infrastructure. One company claimed to have efficiently produced hydrogen for 3 million vehicles currently available, and as distribution costs are only a small portion of the infrastructure, such a player is likely to become a competitor. Therefore, collaboration seems a wise option, and the creation of a vision for hydrogen mobility in Noord-Holland is an important pre-requisite. As

## **Economics**

In order to upgrade the steam methane reformer to meet the required quality standards investments will be needed, which will have to be negotiated with the operating gas company. This source is found to be economically competitive with regard to market projections of hydrogen production costs.

### Future (2 PJ / 14 PJ pathways)

By the end of the market introduction phase, the hydrogen demand is expected to start exceeding the excess capacity of the SMR. Presently it is evident that hydrogen powered mobility is a growing market that requires a growing hydrogen sources. This reduces the risk of investments in a required PSA installation at Tata Steel IJmuiden.

## **Technology**

The PSA system is considered proven technology, however will take several years to become operational. The main technological requirements are the PSA unit, adsorbents, COG and hydrogen compressors and a storage facility. The initial pressure swing adsorption unit and additional components will need an initial capacity of at least 150 tonnes/year and up to 5000 tonnes/year during market commercialisation. The unit is modularly scalable to growing demand. During a mass market uptake, the unit should be scaled to separate all hydrogen molecules, delivering a capacity of over 35,000 tonnes/yr.

## **Economics**

As hydrogen separation and distribution is not core-business to the company and requires initial investments of up to €19 million, external funding will be needed. No concrete public funding options were found during this research for such a unit. Funding for hydrogen mobility is mainly related to infrastructure and applications, and recent examples include funding from the Ministry of Infrastructure and environment. A project finance plan should be configured, preferably with leverage through loans. The creation of an entity or consortium such as a public-private partnership that controls the development process of financing is a favourable option, and during the initial phase this should be a “coalition of the willing”. Tata Steel can aim to include investments needed for a PSA unit within such a consortium.

## Governance

One company has expressed the ability to deliver all components necessary for a PSA unit. In a future hydrogen cluster for the province of Noord-Holland, this party will be included and technological knowledge and information can be obtained. A coordination body should be in place to govern the cluster during commercialisation and mass market in the form a consultancy or regional government. Regular meetings will take place to stimulate the quality of inter-firm relationships within the cluster and should be characterised by open-communication. Tata Steel should emphasize the need for access to specialized information regarding PSA technology and infrastructure, and combine its expertise with cluster partners to create complementarities of joint-marketing and joint-bidding. Delegates from the Province of Noord-Holland, public, private and strategic investors should actively be pursued and invited to cluster meetings.

## Recommendations for future research

From a sustainability perspective, the main question arises whether by-product hydrogen from coke oven gas is a desirable source. In the case of Tata steel, the waste gas is currently utilized for electricity production and heating furnaces. Therefore, additional natural gas would possibly be needed should hydrogen be separated. A suitable methodological approach to uncover the environmental impact of by-product hydrogen separation is Life Cycle Analysis, and could be valuable to scientific research in the field of industrial symbiosis.

Such a study can also be of value to Tata Steel Ijmuiden. During research, a technical report on the definition of 'CertifHy Green' hydrogen was published in 2015 under the European Commission, which states the Guarantee of Origin eligibility criteria for both 'Green hydrogen' and 'Low-GHG hydrogen'. In a discussion with ECN (Marcel Weeda), under the CertifHy methodology hydrogen needs to be produced with 65-70% less CO<sub>2</sub> than directly from Steam Methane Reforming. The approach presented in the report finds its foundations Life Cycle analysis, and seems highly relevant to uncover where by-product hydrogen from COG would stand in terms of sustainability. With a positive outcome, this could strongly influence the perception of stakeholders with regard to the hydrogen source at Tata Steel Ijmuiden.

During this research, several financing options were presented for hydrogen infrastructure and refuelling station roll-out. However, encouraging industrial eco-innovation such as industrial symbiosis is a difficult task. In a well cited article Bocken, Short & Evans (2014) introduce eight sustainable business model archetypes, one of which is 'creating value from waste', with industrial symbiosis as an example. Should by-product hydrogen from COG be a desired option based on a life cycle analysis, research into such sustainable business models may be interesting to pursue.

A hydrogen mobility market and the development over time can be regarded as a complex system. The notion of Complex Adaptive Systems (CAS) views such systems as a dynamic network of many agents (representing for example firms, regions or nations) acting in parallel, and constantly acting reacting to what other agents are doing (Waldorp, 1992). Agent Based Modelling is a powerful tool that enables capturing the capture of complex structures and dynamics inherent to complex adaptive systems. Research by Nikolic (2009) has found this tool to be

particularly applicable to industrial clusters, without knowing how different aspects affect each other. By identifying how individual participants (such as hydrogen infrastructure companies, public authorities) of a potential cluster might behave, it is possible to construct an agent based model and obtain the global behaviour of the system. This could provide valuable insights for a hydrogen cluster.

For this research the hydrogen mobility market was chosen as a scope. However, as hydrogen is a resource for a wide variety of other processes and industries, it is important to look into other applications for by-product hydrogen. The main current alternative uses for hydrogen have been identified and summarized in a table in Appendix C.

Overall, this research was proposed to fit in between a scope of a so called hybrid industry adapted from research on Japan's Eco-Town projects. The concept of hybrid industries is interesting as it relates to transitional system towards reaching climate goals. In short, a transitional system fits in between the current system heavily reliant on fossil sources, and a future desirable system where fossil fuel usage declines and relies more on renewable sources of energy and materials. In this case, the transitional system would be by-product hydrogen as a source for a more sustainable mobility sector. An interesting research focus could be on other types of configurations between industry and urban areas regarding energy and materials that can also be placed in a transitional system. In the opinion of the author, it is mostly a matter of perspective, but when placing research topics within such a view it provides a perspective and a long-term orientation towards desirable future economies.

Lastly, such a hybrid industry seems to be more necessary in a developed economy where infrastructures for mobility are in place and a steel plant reuses waste gases in an efficient way. This is often not the case in developing countries such as China or India, where waste gases are often flared leading to quite an environmental hazard, and diesel or petrol infrastructures are less in place. In such circumstances and possible remote regions with steel plants, opportunities for developing a hydrogen infrastructure for mobility using by-product hydrogen could be much more interesting and worth looking into.

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### Appendix A: Current coke oven gas usage

Today coke oven gas at Tata Steel IJmuiden is used for its heating value in internal operations at Tata Steel IJmuiden and for electricity generation in an adjacent power plant as shown in Figure 28. TSIJ and the owner of the power plant have a “tolling agreement”, wherein TSIJ is owner of the COG and electricity, and pays a fee for the electricity production. TSIJ delivers all gases for the power plant and all electricity is returned to TSIJ. Any electricity surplus is sold to the grid and any electricity shortage is bought from the grid. Depending on the prices for natural gas and electricity, TSIJ chooses to substitute for natural gas, or to increase electricity production.

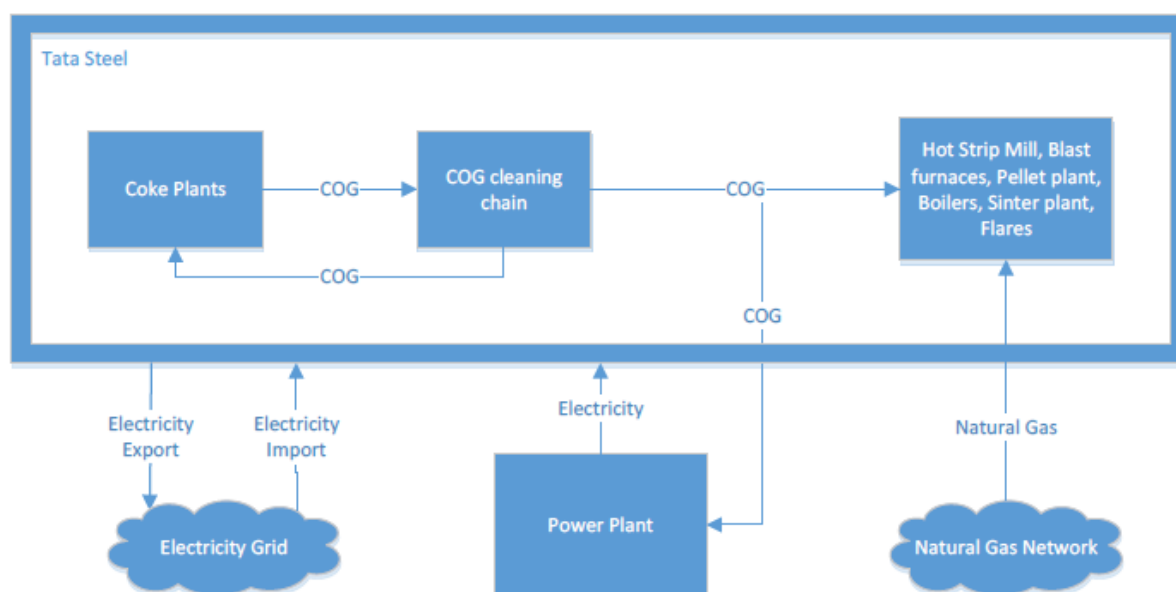


Figure 28 Current coke oven gas usage at Tata Steel IJmuiden

## Appendix B: Pressure Swing adsorption process

The Pressure Swing Adsorption (PSA) cycle follows a number of steps that govern the performance of the process. The steps followed by each column are shown in the form of a flow sheet in Figure 29 for the PSA cycle proposed in the current work aiming at high purity  $H_2$  with the best possible recovery (Ramani, 2016).

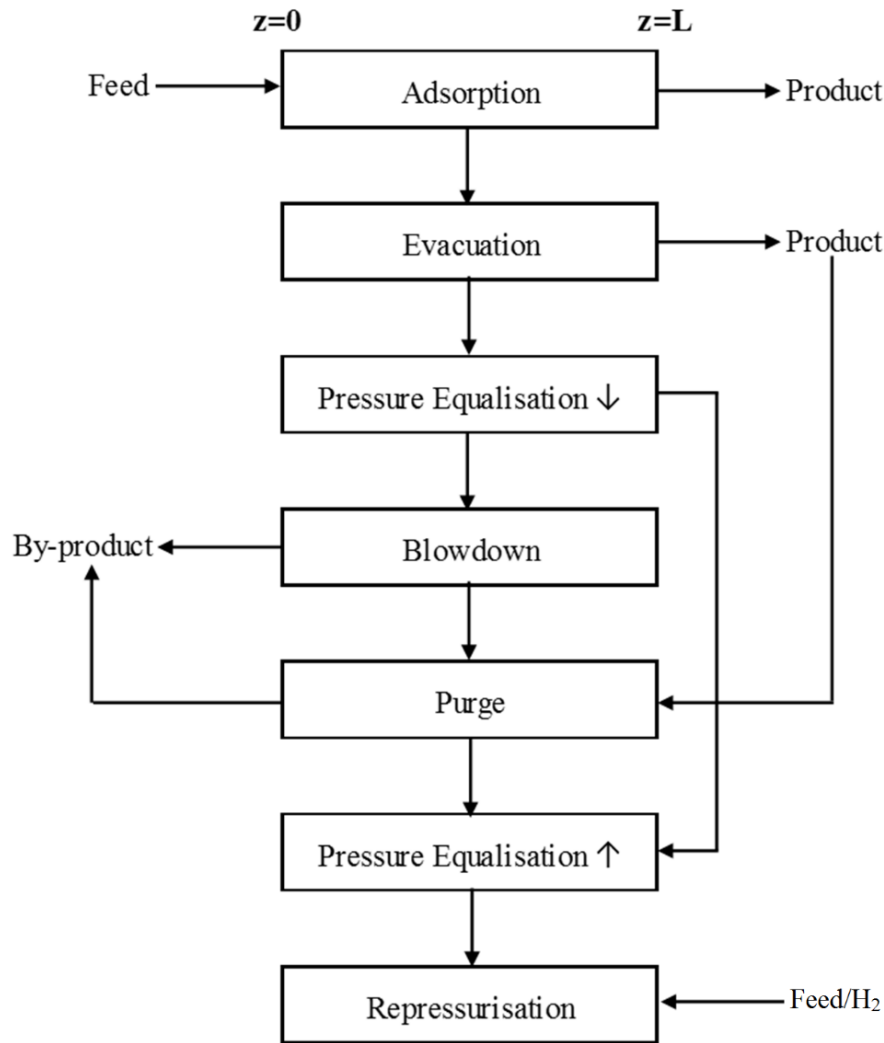


Figure 29 Flow sheet for different stages of PSA system (Ramani, 2016)

A Pressure Swing Adsorption cycles consists of the following steps (Ramani, 2016):

1. Adsorption: The Coke Oven Gas feed enters the column and the product end ( $z=L$ ) is opened. The heavier components are adsorbed while  $H_2$  rich raffinate is collected from the product end.
2. Evacuation: The feed end ( $z=0$ ) is closed and the column pressure is reduced to an intermediate pressure  $P_1$  by leaving the product end opened. The aim of this step is to collect as much  $H_2$  as possible while retaining heavier components in the column.

3. Pressure Equalisation ↓: The feed end remain closed and the column pressure is reduced from  $P_i$  to an equalisation pressure  $P_{EQ}$  by connecting the product end to a column that is in its pressure equalisation ↑ step at that instant of time.
4. Blowdown: The product end is closed and  $CH_4$  enriched product is collected from the feed end by decreasing the column pressure to  $P_L$ .
5. Purge: The  $H_2$  rich evacuation product is depressurised to  $P_L$  and fed through the feed end. The remaining heavier components present in the column are purged out and collected at the product end so that the bed is free of heavier components.
6. Pressure Equalisation ↑: The product flow from the pressure equalisation ↓ step enters the column at the product end with the feed end closed hence increasing the pressure from  $P_L$  to  $P_{EQ}$ .
7. Repressurisation:  $COG/H_2$  is introduced into the column at the product end with the feed end closed, thereby raising the column pressure to  $P_H$  and making the column ready for the next cycle of adsorption.

The state of the column at the end of a step is taken as the initial condition for the subsequent step. The sequence of steps is repeated until a cyclic steady state (CSS) is reached. Considering CSS behaviour, only one column each of activated column and zeolite LiX bed is simulated in time assuming all the other columns behave in the same manner.

## Appendix C: Other markets – Industrial Applications

Aside from possible (future) mobility applications and in line with the notion of more 'traditional' industrial symbiosis, there are several primary industrial applications. As mentioned, currently hydrogen is an important feedstock in the chemical and petroleum industry, where ammonia production with hydrogen to manufacture fertilizers account for around 50% of total use, and crude oil processing in refineries for around 40% of the total 700 billion Nm<sup>3</sup> gas business (Ball & Weeda, 2015). The industrial applications are only two examples, but there are more.

The use of industrial hydrogen can be broadly divided into the following categories:

- 1) As a *reactant* in hydrogenation processes (where hydrogen is used to produce lower molecular weight compounds, saturate compounds, crack hydrocarbons or remove sulfur and nitrogen compounds)
- 2) To chemically remove trace amounts of O<sub>2</sub> to prevent oxidation and corrosion
- 3) As a fuel in rocket engines
- 4) As a coolant in electrical generators to take advantage of its unique physical properties

Hydrogen as a reactant is by far the largest proportion in terms of application. It incorporates usage in chemical and petroleum, which as noted is the vast overall majority. This next section will give an overview of these applications with a short description. As this section merely shines a light on potential market applications there is no need for much detail in this stage.

Application	Short description
<b>Petroleum Processing</b>	In the petroleum industry, hydrogen is reacted with hydrocarbons in many ways including hydrocracking and hydroprocessing. These take place simultaneously to produce refined fuels, removing sulfur and nitrogen compounds
<b>Petrochemical production</b>	Many petrochemicals are produced using hydrogen, especially methanol. Hydrogen and carbon monoxide are reacted over a catalyst at high pressures and temperatures. Other uses include: <ul style="list-style-type: none"><li>- Butyraldehyde from propylene</li><li>- Acetic acid from syngas</li><li>- Butanediol and tetrahydrofuran from maleic anhydride</li><li>- Hexamethylene diamine from adiponitrile</li><li>- Cyclohexane from benzene</li><li>- Polypropylene</li><li>- Plastics recycling (molten plastic is hydrogenated to crack it to produce lighter molecules which can be reused to produce polymers)</li></ul>
<b>Oil and fat hydrogenation</b>	Hydrogen is used to decrease the degree of unsaturation fats in oils.

<b>Fertilizer production</b>	Ammonia is produced by reacting nitrogen and hydrogen, and is seen as the backbone of the fertilizer industry, consuming around 50% of all hydrogen produced globally.
<b>Metallurgical applications</b>	Hydrogen is used in the reduction stage of the production of nickel, where nickel in sulfate solution in presence of ammonia is converted to elemental nickel, leaving ammonium sulfate.
<b>Electronics industry</b>	Hydrogen is used by wafer and circuit manufacturers to reduce silicon tetrachloride to silicon for growth of epitaxial silicon.

## Appendix D: Expert Interviews

*Meeting Tata Steel IJmuiden & Pitpoint*

*Date: 28<sup>th</sup> of June, 2016*

*Attendees:*

*Tata Steel IJmuiden: Gerard Jägers, Andre van der Ploeg, Balan Ramani, Jochem de Jong*

*Pitpoint: Erik Büthker, Oscar Voorsmit*

.....

*Before getting into the real topic, Pitpoint will present themselves first.*

Small introduction about Pitpoint and what we do. We are not only focused on CNG, but a wide range of alternative fuels. We have a vision that we only supply clean fuels as of 2030, and no fossil fuels anymore. We are currently working on achieving that goal. A little bit about the history: You probably know we started in 2007 as CNGnet, in 2011 we built the first LNG refuelling station in (Zwolle?). Then we were part of Balanidam?? (subsidiary). In June 2013 different companies were merged together, and in september 2013 we were taken over by Benzis capital, who bought us out from Balas nidam, and they established the European clean fuel company, and we changed the name in January 2016 to Pitpoint, in order to cover all the fields of LNG, CNG, hydrogen, electric, biomethane.

Competitors in the market – for CNG it is Orange gas, for hydrogen there are no big players at the moment active I think.

Moving on – Air quality and sustainability. Local air quality is an issue, global warming is an issue, and limited resources – so we need a transition from fossil to sustainable fuels. We have different fuels, CNG, LNG, hydrogen and electric. We have a concession in Utrecht to supply electric chargers.

This is how the map will look like in the Netherlands, Belgium and a little bit of Germany

For CNG network. In Ameland 8 buses are running on CNG.

This is the station in Helmond (hydrogen) – on the left you see the electrolysis unit, on the right is the compressor unit and storage. I believe the electrolysis unit is from hydrogenics.

Here is a slide of battery electric refuelling infrastructure. We have some issues with customers who do not mover their vehicles, so we are experimenting with systems where when the car is full you get a message, and if you do not move your car you will pay for a parking tariff.

This is the LNG station in Zwolle (liquefied natural gas) etc.

We have a joint venture with primagas where we use Primagas for the logistics of the LNG and we build the stations. Some of our projects I'm very pleased with the left

picture – ferry to Texel – running on CNG. This uses the dual fuel, with a diesel engine that injects natural gas.

Some canal boats in Amsterdam, but our focus is taxi fleets for disabled people, or school children with specific concessions. That is the way to build up your market. Where you have a basic number of vehicles at your station, then you can build up the market very easily.

Also our track record on public transportation – Started here in IJmond, Haarlem/Velsen. Here 80 buses of Connexxion are running on CNG, and that means you need to guarantee the availability of the refuelling station. Because buses are refuelled every day and night.

That made also some interesting challenges in Den Haag, where we refuel about 180 buses everyday, and Arnhem Nijmegen, that are about 200 buss everyday (CNG). Here you learn a lot about how to operate your station and to guarantee availability. That means also you need to convince the bus companies that are you a able to do it. They are used to diesel as the have always run on diesel, and now they have to change to another fuel, they are not very open in that approach.

Our approach – what we do, from the production of bio methane, we are active in the design, we build, we finance, we maintain, we operate and we guarantee 24/7 service. Also for the T-zone, it was very interesting, they came with a question to refuel them with LNG. We made a calculation for them on what the fuel costs are and investment requirements and what the operational cost will be for them. We came to the conclusion that CNG is a much better option for them, because the boat is the whole night in the harbour. So you have the whole night to refuel the boat. And to transport LNG all night to the island is more difficult. And the logistic cost is higher. These are types of calculations we make for the customer.

Reliability, is the most important.

Core business is building a network of stations and guaranteed availability. What we also have is an online control of all the station. We have a centralised control of the stations, with sensors at the stations. So when a parameter is running out of specs, we can already take action to prevent fall out. That is the way we operate all our stations.

*You say here there is one hydrogen station?*

The only hydrogen stations operational are in Rhoon and Helmond. If you want to have a hydrogen car these are the only stations possible.

So we also have our own service. We have our own maintenance crew running through the Netherlands. That's the way we can guaranty availability of more than 98%. And that is VERY important to introduce alternative fuels. The customer is

already taking a risk in his opinion to change over to an alternative fuel. And when you then enter in that stations and it is not working, the you have a big problem.

Our approach – we do the investment, we cover the start-up costs, we do the design and build ourselves. We have our own engineering department. I'm personally deeply involved in the standardisation work. I'm the chairman of the Dutch standardisation committee for hydrogen refuelling stations, and also internationally active in setting up standards for hydrogen refuelling stations.

*Are you in one of the working groups of the NWP?*

Yes, but the NWP is not active in the standardisation work at the moment, so we have in the Netherlands the **PGS-35?** I am the chairman of the PGS-35 and active in the international standardisation, that is the **ISO TC 197** dealing with the same subject. But that is the international group. The ministry is also stimulating that we bring our expertise in the Netherlands into that international group. This makes some difficulties in understanding each other, because in NL we are very developed in risk assessments, and in determining safety distances and in America, Canada and Japan they have a completely different approach. That is not always easy to overcome.

So that is about permitting, certification and exploitation. We as I said we hire a piece of land at the refuelling station, we install there equipment like a container or a complete building with a paying terminal and it is directly controlled by us.

So what can we do? Analysis of the location, Logistics, capacity calculations, permitting, and very important the marketing. Because when you put a refuelling station somewhere and you are sitting there and waiting for the vehicles to come – they won't come. That is our experience from CNG.

This gives you an idea of what we are doing, just an impression on what our company is. This is the way we also want to develop the hydrogen infrastructure.

*Gerard Jägers: And why are you now looking for extra hydrogen? The filling stations you are working on, you already have an idea on where it will come from.*

Yes, but we like to develop the network of HRS based on customer fleets. We are in discussion with the province of Noord-Holland, where there are possibilities with connexion together with their bus fleet. There we see opportunities to combine activities and set up a project. This is not in this list yet. Basically we are just looking for sources of hydrogen. What you see is some parties say that if you want to build an HRS it must be from electrolysis and it must be 100% green. Basically our vision is that we first need to work on the infrastructure and it doesn't need to be 100% green at this point in time. 100% green will be in the future with much more renewable energy and excess REE. So right now we are just looking for sources of hydrogen.

For instance, that is how we got into contact with Akzonobel in Delfzijl. Because they have they're excess of residual hydrogen and we can make use of it.

*GJ: now I would call that residual hydrogen as fairly sustainable, and I would call our hydrogen from COG more or less sustainable, the SMR from Linde is not sustainable so that would only be a temporary option.*

Yes, but temporary – if you compare it to CNG, it took us ten years to build up a CNG network, and now we are at a stage that we change over from fossil gas towards biomethane. I think for hydrogen it is nice to have directly as clean as possible, but nobody wants to pay for it. It is a route, a transition towards sustainable hydrogen. First you need the infrastructure, and without modification of the infrastructure you can supply the infra with supply hydrogen.

*GJ: Do we have enough surplus capacity for one filling station, or two? About 450 cubic metres/hour*

*BR: And what is the capacity of a station?*

OV: That depends on the customer. What we are now starting to look at is fuelling stations for 20 buses. And if you are looking at 20 buses you must calculate – 20 buses, say 24 kg a day, and then let's say not everyday of the year so 250-300 days. This way you can calculate volume. And if you are looking at a 700bar station for personal vehicles that refuels a minimum of 20 cars a day, and 20 cars need 4-5 kg each. So that is a minimum station for only personal vehicles for let's say the first station. I personally don't believe in the near future there is going to be bus stations of let's say 100 buses. The first step is to scale up to 20 buses. So these are the dimensions you would be looking at.

*BR: With our capacity, it is like 500 tons of hydrogen we could produce per year, so we could supply like 48-50 buses per year.*

*EB: At what pressure is this SMR hydrogen?*

*AvdP:* It is fed to the grid at 10-11 bar. So you would need to compress it. Major investments that are required are to further purify the 3.0 hydrogen to 5.0 to use it in fuel cells.

*EB: And can that be done with a pressure swing adsorption unit?*

*BR:* Yes, we do have an existing unit there, but we currently do not need the necessity of 99,99999 (5 nines) purity, so we restrict it to the 3 nines for current process. Should it be necessary we could increase it 5 nines, but we would have to change the adsorbents and the capacity first. But the same installation we can modify it.

*EB: Ok, that is also our situation with biomethane production, what we do over there for example the meerlanden near Schiphol we have a cooperation with them. They*

*built a digester and we operate the upgrading facility to upgrade the raw biogas to biomethane. Then you can use it directly in the vehicle. That type of activity suits us very well, we want to be in control of the whole supply chain. That is the reason why we also participate in biomethane production facilities, to get control of quality and availability of biomethane. I see the same chain for hydrogen.*

*JDJ: and who is responsible then for the transportation of the fuel?*

For the biomethane that is directly used at the facility is injected into the grid. On the other hand we have a cooperation with Primagas for LNG, so maybe they can transport it. But the logistics, Linde Gas can also transport it, that doesn't matter for us.

*JDJ: But you would need some sort of collaboration?*

OV: But if you are currently looking at Groningen, everybody is always talking about Groningen because that is a well known international city, but the hydrogen station is actually going to be in Delfzijl, because Delfzijl is next to the plant (AkzoNobel). So we don't need to transport it, we only need a pipeline of a few metres. But that is more like a pilot project, because two buses are going to be operational. So if you want to build a station with let's say 20 buses, then we would need to transport it to a depot at the bus operator. I can not imagine that buses would refuel on a Tata site so we would need to transport it to a depot.

GJ: That is certain because our SMR is done more or less in the center of the area and we don't let buses onto the area. It would even be a problem to get it out of our area with a Linde Gas truck, many obstacles would have to be solved.

*OV: for my understand – the SMR is used for to produce hydrogen with a quality of 3.0 which should be upgraded to 5.0 for fuel cells. This is now only used for the internal process? Yes. The residual from the COG is another process?*

*JDJ: yes, that is a more long-term perspective. That is a 10-20 higher capacity than the SMR.*

*OV: And what is it used for now then?*

*BR: We use it mainly for heating, and we supply 2 PJ to Nuon for power production.*

*OV: so that is mainly burnt in the gas turbine?*

Yes

*OV: and what is the reason for the long-term perspective?*

*BR: it is a very dirty gas, it is from coal so it has many chemicals. However it is technically feasible, but we don't know whether it is economically feasible. Compared to SMR it is much more expensive.*

*OV: in all the discussions about hydrogen in NL, we always hear that the Tata hydrogen would be very dirty hydrogen, but I guess people are then referring to the COG hydrogen and not the SMR hydrogen?*

*GJ: But also the hydrogen from COG will in the future be able to reach 5 nines of purity. That is what Balan Ramani is currently modelling.*

*BR: currently the gas will poison the fuel cells. But our goal is to make in 5 nines, which is feasible.*

*JDJ: with the needed technology for producing hydrogen from COG, are you interested in investing in those kind of things?*

*EB: What I showed is in other markets it is not strange for us to make these investments, but it all depends on the business case behind it. If we can then supply 20 buses with a local hydrogen source and bus operator here, then it is a feasible project. But we are only investing here to make pure hydrogen without a market then ofcourse not.*

*BR: and biomethane you mean just the waste or the first grade/generation biomass?*

*EB: In the Netherlands it is all certified to the standards, And there is also a certification scheme which also shows the sustainability of the feed. There is a lot of confusion around various generations of biofuel. At NGO's it is mentioned that Pitpoint uses crops from the field to produce gas, but that is simply not true. It is all certified. Certification scheme is there, so I send them the scheme and they are surprised.*

*GJ: You know now what we have available more or less and what is needed to produce hydrogen here and how Linde Gas (SMR) produces it, so you have some idea about the cost price. If you would like to use it we would have to involve Linde in this discussion. And the study of Balan will show how it is with the residual H<sub>2</sub> from COG which is more or less sustainable.*

*EB: May I ask this question in a different way? If Linde is operating the steam reformer, what is the involvement of Tata?*

*GJ: Linde has built the installation fully for us, Tata is owner.*

*AvdP: We do not own it. We pay a fixed fee for building maintenance and operation. We provide the natural gas, so everything that comes out is ours. They are more providing us a service.*

*GJ: Why are we involved. It is also difficult to get it from the SMR to somewhere you might need it, there are some logistical aspects, safety aspect which are ofcourse very important, and I see it as a stepping stone for the bigger picture project of Balan.*

*That's why we are interested. And why we are interested in the study of Balan, because right now it is mainly used for electricity production but which in the long term future is not the best way of utilization with this gases.*

*BR: Also, it is not an efficient way, maybe if you have a fuel that has 20-30 vol% hydrogen it is better to burn it, but this has a much higher content so it is a shame to burn it.*

*EB: Are you already involved in subsidy projects which studies governments to pay for these kind of things?*

*OV: a while back I provided you with some prices and you said the chances for subsidy were very slim for Tata?*

*GJ: Not feasible, the investment are so high with such limited application. And besides, these subsidy requests are so difficult, we didn't even have time to do it.*

*EB: What we do is we hire a company to perform the subsidy question.*

*GJ: we have our own specialists for this, but everything was too vague at this stage.*

*EB: But I think there are some possibilities to set up a business case. Look what is needed, and get some support from the government. There are some options.*

*OV: I basically look at this conversation as a first introduction, so at least we know each other. We simply look at what is going on in the field, and if we see any opportunity we can set up an initial business case. And if you see or hear anyone that is interested in using Tata's hydrogen for refuelling, you know we are able to build at this stage.*

*GJ: I think the next step is up to you, you will see whether things are useful here as an opportunity. And if you want to have our contacts with Linde we can have a next discussion. We had quite some talks with Linde, but they are decreasing their efforts. Our natural contact left the company, so we don't have an easy contact anymore.*

*EB: they also stepped out on LNG, which is strange in this time.*

*BR: for your hydrogen fuel stations what is the pressure you expect? In the initial case of SMR we have it at 10-12 bar, but what is your expected pressure?*

*OV: We would do the conversion. 10 bar would be fine, we would be investing in the infrastructure, which also means the investment in the compressor. Basically, if we would have a customer, you would supply us the hydrogen with a certain quality, which we would then supply the customer with. It is up to them which quality/pressure they require. There is however a difference between supplying it at 1 or 900 bar. The compressors have a different range. 1 bar or 10 bar can already make a big difference for us at the compressor. Sometimes the pressure is that low that we first*

*have to install a booster to boost it up to a certain pressure in order to put it into a larger compressor. So the higher pressure you deliver it, the better the business case will be. To manage expectations, there is not a lot of money coming yet from hydrogen. That is the reason we only have Rhoon and Helmond.*

*EB: You are also talking to the province of Noord-Holland about setting up a project?*

*GJ: They know that there is hydrogen here. But I don't see much power. Not much progress. Some people like Jack van der NEs are thinking ahead, and he might also be thinking about having fuel stations for hydrogen. Also Jacqueline Kramer, former ministry of Environment, she also tries to drive the hydrogen and fuel cells. We don't know how fast she could get this running.*

*EB: For us it is also depending on the business case if there is no fleet available. Because we are not going to invest in a fuelling station if there is no fleet.*

*JDJ: And you say you are also talking to Connexxion in Noord-Holland?*

*EB: Yes, because we are doing the current concession with them. And the current concession is on CNG and biomethane, and we were also at that symposium for new developments and had some talks with parties involved. They also say: yes we want to switch to electricity and clean buses, but for the same budget. When you compare the diesel bus to the hydrogen bus the cost price of a hydrogen bus is 1M euro, and a diesel bus costs 200.000 euro.*

*OV: So the focus for buses is not necessarily on hydrogen buses. From the discussion from the NWP OV group, there might be a grant coming for 100 buses. We are also looking at personal vehicles.*

*EB: But then again, even if the buses will be subsidised, you are still at around double the price of a normal diesel bus (4k -5k). Everybody says, and even looking at predictions from ECN, that even costs for refuelling stations will drop dramatically. They will go down for 40% in future. But my experience with CNG which had the same predictions 20 years ago, the cost price of the stations will go down only a little bit in engineering cost, but the steel block you need to compress the hydrogen will remain relatively the same price.*

*EB: The government should realize that support (financial) is needed in one way or another (driving up price for diesel buses in the form of taxation, subsidies for hydrogen buses.*

## Korte inleiding

Was bij een provinciehuis meeting aanwezig, die redeneerde als volgt: De hoogovens hebben toch waterstof, dus het enige wat wij nog moeten regelen is bussen. Jaap vond dit een beetje kort door de bocht.

Wat betreft waterstof is er al symbiose die aardgas vervangt. Dit betekent dat de value van het waterstof ook de value is van aardgas. Dus als je de SMR wil vervangen, dan wordt dat lastig. Is niet evident omdat SMR zo doorontwikkeld is dat de efficiëntie met kooksofengas niet te evenaren is. Net zoals er geen gratis elektriciteit bestaat, bestaat er ook geen gratis afvalgas.

Air liquide heeft zelf ook gekeken naar een afvalstroom om daar waterstof uit te halen, daar was het economisch niet rendabel. Bij COG ligt de waterstof content echter vele malen hoger, dus is dit wellicht economisch interessanter.

Wat is de druk van het waterstof? PSA bedrijf je vanaf 16 bar ongeveer. Het gas moet gecompriëerd.

Wat zijn de vloten waarop gericht moeten worden? Air liquide kijkt vrij breed naar vervoersmiddelen. We kijken naar elektrische voertuigen, waarbij je een heleboel kracht voertuigen niet op batterijen kan laten rijden. Als voorbeeld een vuilniswagen, deze kan je prima elektrisch laten rijden, alleen die kan niet zoveel batterij capaciteit meenemen om die laadbak voldoende aan te sturen. Hierdoor heb je een elektriciteitsvoorziening aan boord nodig. Hier wordt naar gekeken en ook mee geëxperimenteerd in Helmond (waterstofvuilniswagen).

Tweede mogelijkheid is bussen. Als je kijkt naar de stadsbuswereld (GVB, RET, etc), dan zie je dat zo'n bus met een gemiddelde snelheid van 17km/h door de stad rijdt. Dat maakt het ideale kandidaten om op batterijen te laten rijden, alleen komen ze dan niet zo ver. Het idee hiervoor is om bussen dan met een behoorlijke batterij capaciteit te laten rijden. Maar ook uit te rusten met een kleine fuel cell die continue elektriciteit produceert en de meeste efficiënt mogelijk te laten werken. Dat betekent dat hij continue produceert, die vult de batterij bij maar de batterijen doen het werk. Bij dit soort lage snelheden is dat heel goed mogelijk.

Als je kijkt naar streekvervoer bussen, net zoals bij gewone auto's, daar heb je een grotere fuel cell nodig en juist kleinere batterijen. Daar kijken we momenteel naar.

Als je kijkt naar het vrachtverkeer hebben we in de haven in Rotterdam ontzettend veel vrachtverkeer die ook zo'n lage snelheid hebben als je de stadsbussen. Zoals bij terminals of kades in de haven. We kijken vooral dus naar dat type voertuigen die een kleine fuel cell hebben die het meest efficiënt de waterstof gebruikt, waarbij de

accu continue bijgeladen wordt. Dat is ook goed te doen want het zijn in principe nesten, dus als je een vulstation plaatst – die bussen komen daar altijd weer terug naar toe. Dit geldt ook voor taxi's en vrachtverkeer in de haven. Zo creëer je een gecontroleerde afname van waterstof. Deze voertuigen komen volgens schedule hun waterstof ophalen.

Een interessante afnemer is Schiphol bij de Zuidas, dat gaat meer over stationaire toepassingen. Op de stands (dus niet bij de gates) werken ze nu veel met dieselgeneratoren, daar willen ze natuurlijk graag vanaf. Geografisch is Schiphol ook een relatief klein gebied, dit is gunstig voor distributie.

Als je kijkt naar het gebied van Tata aan de ene kant en Schiphol aan de andere kant heb je daartussen een redelijk overzichtelijk gebied (gemeente Haarlem, en een stukje van Amsterdam). Je kunt kijken of je daar niet een leiding structuur kan aanleggen, waarbij een centraal vulpunt maakt en vanuit daar distribueert maar verschillende vulpunten. Je kan zeggen, ik leg van Tata een leiding naar Schiphol, omdat dat mijn grootste gebruiker wordt (dat is ook een hub voor bussen). Dan kom ik ook langs Haarlem waar ik aftakking maak naar de busremise in Haarlem. Op deze manier kan je met een relatief beperkte infrastructuur toch een groot gebied bestrijken. Ik weet niet of er transporteurs zijn in die wereld die dat zouden willen, maar zo moet je gaan denken.

*Bij het aanleggen van deze infrastructuur, hoe zit het met eigendom en wat voor samenwerkingen zijn daar mogelijk?*

Ik zit in een werkgroep bij rijkswaterstaat waar we kijken naar infrastructuur. Er zijn drie grote infrastructuur systemen die door rijkswaterstaat onderhouden worden; ons rijkswegennet, rijkswaterwegennet en het railnet. Hiervoor zijn meerjaren plannen. Waar we mee bezig zijn is ondergronds transport als infrastructuur systeem daar in opgenomen te krijgen. Hier mee realiseer je dat dit soort pijpleiding systemen ook meegenomen worden in de planning en allocatie van geld in begroting van rijkswaterstaat.

Je begint namelijk met een minimale afname (bijv. stationaire toepassingen op Schiphol), dit zal nooit de leidingen kunnen betalen. Je zult dus het leggen van de infrastructuur (leidingennet) moeten bekostigen met rijksmiddelen. Daarna zie je dat gebruikers die investeringen langzaam terug zullen/moeten betalen.

Hetzelfde gebeurt met warmwaternet. De infrastructuur van waternetten kan niet betaald worden door de initiële gebruikers, maar je hebt wel die leidingen nodig om te beginnen (kip ei dilemma). Vaak wordt dan de infrastructuur gedragen door de overheid, die op termijn hun geld terug krijgen als er meer gebruikers komen. Enige probleem hierbij is, als het een publiek rechtelijke leiding wordt, dan zullen daar meerder gebruikers op moeten kunnen. Dan heb je het issue met waterstof kwaliteit. Met name deze fuel cells hebben een hele hoge waterstof kwaliteit nodig om te kunnen functioneren en ook langdurig te kunnen functioneren. Koolmonoxide is

eigenlijk het vervelendste ‘gif’ voor fuel cells. Zwavel is wel een issue, maar bij SMR is een van de eerste stappen het ontzwavelen dus is hierbij geen issue. Als je een PSA hebt, dan komt er echt geen zwavel bij.

*Wat zijn andere manieren om infrastructuur te bouwen?*

Je kan ook ter plekke op Tata een vulstation bouwen en daarna de trailers rond gaan rijden. Je kan hier het waterstof zuiveren, comprimeren en via tubetrailers op de weg de waterstof distribueren. Een volgende stap is de waterstof vloeibaar maken, maar dat is een hele dure grap. Het comprimeren naar 300 bar is een vrij simpele stap, daar is wel weer elektriciteit voor nodig, bij voorkeur uit hernieuwbare energie. Die 300 bar breng je dan naar je vulstations. Als je 200 kg per dag nodig is dit een mogelijke oplossing, zodra je naar grotere hoeveelheden gaat wordt het lastig. Het vervelende is als je eenmaal een bepaalde infrastructuur gebouwd hebt is het daarna lastig om weer over te stappen naar een meer centrale infrastructuur.

De overheid is een belangrijke speler bij dit soort onrendabele gehelen om de zaak voor te financieren om uiteindelijk een rendabel system te krijgen.

*Wie moeten er aan tafel zitten om de infrastructuur te realiseren?*

In eerste instantie heb je partijen nodig die de mobiliteit kunnen beïnvloeden. Partijen die dus zeggen: “je zult op waterstof moeten rijden”. Dat is in feite de provincie, deze geeft concessies af voor het openbaar vervoer. Met name voor de gemeentelijke vervoersbedrijven. Probleem is dat de huidige persoon helemaal voor elektrisch is en niet voor waterstof. De pilot met de GVB was een goede pilot, maar is door wisselingen in posities misgegaan.

Een typisch voorbeeld is de taxi’s rondom Schiphol, waarom daar nu allemaal tesla’s rijden is door toedoen van de overheid. Het creëren van de juiste randvoorwaarden is essentieel.

Binnenkort start er een pilot van twee waterstofbussen in Rotterdam. Dit is een gevolg van de concessieverlening waarin Air Liquide voor uitgenodigd werd. In deze concessies kan je de nodige voorwaarden in op nemen.

De eerste fase is het allemaal nog experimenteel, maar in de volgende fase kan je in feite zeggen dat de vervoersmiddelen zero emissie moeten zijn “Gij zult met x aantal waterstofbussen gaan rijden”.

Binnen het zero-emissie verhaal als je kijkt naar Schiphol zijn de stationaire emissies een potentiële kans. Daar loopt veel personeel rondom de dieselgeneratoren met emissies, dat is niet handig. Daar kan je weer aan de hand van concessies zeggen: “Stationaire emissies, daar zal geen CO<sub>2</sub> of NO<sub>x</sub> meer uitgestoten worden.” Op deze manier kan je daar iets mee doen. Dat is overheidsbeleid.

Air Liquide kan de hele technologie leveren, van PSA tot compressie tot vulstations. Daar zijn ze niet alleen in Nederland, twee grote concurrenten. In Duitsland wel de enige. Voor hun is het een puur commercieel belang, zodra het aantal moleculen groot genoeg is zullen ze het doen, zolang dat niet zo is doen ze het niet. Air Liquide (Jaap Oldenziel) bekijkt het zo – als de vraag groot genoeg is, zal de infrastructuur in principe niet gesubsidieerd te worden. Je moet zorgen dat de nesten waar je infrastructuur gaat bouwen groot genoeg zijn om de infrastructuur te kunnen dragen. Dat gaat heel plat over puur over het aantal moleculen.

Air liquide heeft nu in de Benelux twee fully operational vulpunten, namelijk in Rhon en Helmond. In de Benelux zijn ze de enige, het derde station wordt Helmond. Daar moet je je voor aanmelden als je daar wil gaan tanken. Daar wordt momenteel niets mee verdiend. Het zijn demonstratie projecten. In Rhon pacht het bedrijf de grond, de aanleg van wegen worden door rijkswaterstaat betaald. De eigenaar van de gepachte grond waar het vulstation staat kan ook wisselen nav concessie (eens in de 7 jaar, kan langer duren aangezien zelfde partij ook weer de volgende pachtovereenkomst kan winnen). Daar kan je een langere pachtovereenkomst sluiten als je aantoont langer nodig te hebben om met de gepachte grond uit de kosten te komen. Hoe lang dit duurt is puur afhankelijk van hoe snel de voertuigen op de weg komen. Maar los van de pachtovereenkomst blijft de infrastructuur gewoon waar die staat.

In 2011 was er één waterstof auto op de weg met een Deens kenteken, nu in 2016 rijden er 25 voertuigen op de weg. In 2014 ging het station in Rhon open, toen waren er 2 voertuigen op de weg. We zijn van 2 voertuigen naar 9 gegaan in januari 2015. Tussen toen en nu nog ong. 16 voertuigen bijgekomen. Op basis van de voorspellingen zouden er eigenlijk een paar honderd op de weg moeten zijn.

In potentie heb je op relatief kleine afstand een potentieel grote waterstofgebruiker: Schiphol. Schiphol is al aan het elektrificeren. Wat zij uit projecten hebben gezien is dat ze bijvoorbeeld elektrische heftrucks vervangen door waterstof heftrucks. Dit betekent dat de heftrucks maar 2 minuten hoeven te tanken, daardoor heb je maar de helft van je heftrucks nodig. Elektrische heftrucks moeten 8 tot 10 uur opladen (hangt af van laadstation). Deze constructie werkt alleen in een volcontinue omgeving. Zodra je in een dagdienst operatie zit dan werkt het niet meer, dan kunnen de heftrucks 's nachts aan de stekker en overdag werk je er mee. Grote supermarkt ketens werken bijvoorbeeld volcontinue in hun warehouses, dit maakt ze potentiële waterstofklanten. Die hebben echt belang bij dit soort projecten. Dit geldt voor Schiphol ook, als je kijkt naar de elektrische bagageauto's, die moeten ook continue draaien. Daardoor hebben ze er twee keer zo veel van. Eventueel worden ze overdag meer gebruikt dan 's nachts, maar je hebt wel het probleem van laden. Die zou je dus kunnen vervangen door waterstof. Zo heb je meer van dit soort transporttoepassing, en daarnaast nog de stationaire toepassingen.

Daarnaast heb je openbaar vervoer concessies, daar zijn een aantal van door de provincie gedreven. De GVB in stadsregio Amsterdam heeft er eigenlijk een monopolie, maar in Rotterdam is het zo dat de vervoersbedrijven concurreren. Daar moet je dus de gemeente zo ver krijgen dat ze de GVB opdracht geven over te stappen. Daarnaast heb je de streekvervoer die over de zuidargent rijden. Dit betekent dat je vooral eerst met de overheden moet gaan praten.

Laten we even kijken naar de SMR in haven Rotterdam. Momenteel wordt de meeste waterstof gebruikt in klassieke aardolie raffinage. Om twee redenen, 1 om crudes van te voren te behandelen. Hiermee worden de zware fracties vloeibaar gemaakt. 2 voor het schoonmaken van de diesels en de benzines. Je kan je voorstellen dat deze waterstof stroom eventueel gaat verdwijnen aangezien olie gebruik gaat verminderen → 2050 zero-emissie betekent dat we geen benzine en diesel meer gaan gebruiken in dit land. In dat opzicht is dat de dood voor raffinaderijen. De infrastructuur zal dus anders ingezet moeten gaan worden om nog steeds waterstof te transporteren, alleen zal die een andere bron hebben.

In de staal industrie ligt dat net iets anders. Daar zal het staalproces waarschijnlijk veel langer dit bij-product opleveren. Als je de waterstof eruit kan halen, kan de reststroom die overblijft nog steeds naar de Nuon's van deze wereld. De klassieke centrales zullen waarschijnlijk ook na 2050 nog steeds bestaan omdat je toch ergens moet balanceren als de wind ineens wegvalt of er een minder zonnige dag is.

Air Liquide levert ook waterstof aan een biodiesel fabrikant (Nestoil?) Die willen een efficiëntie project doen. Die willen uit een reststroom waterstof halen en die terug stoppen in hun proces. De driver hier is dat ze minder waterstof hoeven te kopen omdat ze het uit de reststroom kunnen gebruiken. We gaan uiteindelijk toch door een transitie heen waar we emissieloos bedrijf voeren.

Het uitgangspunt voor Tata is voornamelijk economisch, waarbij ze het grootste deel van het kooksofengas gebruiken als vervanger van aardgas, en de balancerings (overschotten) gebeurt door Nuon. Dit betekent dat de afvalstroom momenteel al een behoorlijke waarde heeft.

Een andere case in Delfzijl met Akzo Nobel: Daar wordt dmv electrolyse een gigantische hoeveelheid waterstof geproduceerd. Deze is echter zo groot dat investeringen om dat allemaal te zuiveren worden bemoeilijkt omdat het moeilijk is zo'n groter afnemer te vinden. Ook zeker omdat de waarde die waterstof nu heeft hetzelfde is als de waarde om er elektriciteit van te maken. Daar zijn ook discussies geweest met lokale vervoersbedrijven om het in te zetten voor mobiliteit. De bron ligt echter in Delfzijl, geografisch niet een gunstige plek. Ook daar moet infrastructuur gebouwd worden, ga je dan een leiding langs het eemskanaal leggen of met tubetrailors werken?

Groot inzicht, er moet een wil zijn vanuit de overheid om te subsidiëren. Vergeleken met Scandinavische landen (Denemarken) waar waterstof daar zijn ze erg

gevorderd. Dit komt met name doordat ze daar erg ver zijn gegaan in het duur maken van benzine en diesel auto's. En een belastingvoordeel geven aan de aanschaf van bepaalde elektrische/waterstof auto's. Ook voorwaarden als gratis parkeren etc. Op deze manier maak je het ook aantrekkelijk voor consumenten om over te stappen. Als je dat koppelt aan OV projecten dan komt dat snel op gang.

Toepassingen: drie categorieën

- OV
- Stationaire toepassingen ( Schiphol)
- Lokale specifieke voertuigen
  - o Schiphol
  - o Tata

Partijen nodig:

- Tata
- Provincie
- Stadsregio Amsterdam
- Infrastructuur bouwers
- Schiphol (overheids NV)

Eigenlijk moet je politici zo ver krijgen om het op de agenda te zetten. Dan komt er druk te staan op de provincies. Als een ambtenaar niet wil dat iets gebeurt dan gebeurt het niet. Ambtenaren beïnvloeden de politici dus die moeten het ook willen.

Schiphol schrijft concessies uit, dus die kunnen bepalen wat er daar rond gaat rijden. Zo kunnen zij de partijen (luchtvaartmaatschappijen) beïnvloeden. Rol Schiphol is eigenlijk dus dezelfde rol als van politici in de provincie.

*Hoe zit het de bereidbaarheid van potentiële kopers om waterstof aan te schaffen vanuit kolen?*

De eerste vraag die ons altijd gesteld wordt is?? 56:45

Bij de infra in de Benelux hebben we een heleboel waterstof producenten, waarvan een groot deel SMR, maar ook een aantal groene producenten. We werken aan een waterstof certificerings programma waardoor we kunnen zeggen welke waterstof carbon vrij is. Net zoals je bij elektriciteit hebt, elektriciteit die uit je stopcontact komt kan groen/grijs/zwart zijn. Voor BV nederland maakt het uiteindelijk niet uit waar de waterstof vandaan komt. Als een producent x% groen heeft betekent dat dat de rest van NL geen groene elektriciteit heeft, dus voor Nederland zelf maakt het niet uit. Dit is ook weer een gebied waar heel veel consultants veel geld verdienen terwijl dit helemaal geen meerwaarde heeft.

In Nederland produceren wij al genoeg carbon free waterstof om drie miljoen auto's op de weg te laten rijden. Electrolyzers gekoppeld aan wind produceren in het

Netwerk van AL. Dit door electrolyse van zoutzuur, als elektriciteit groen is is de geproduceerde waterstof gewoon groen. De helft van waterstof dat uit SMR wordt geproduceert komt uit water (1 methaan molecuul en twee water moleculen?). Een van de grote eye-openers in de waterstof wereld was dat we niet genoeg groene elektriciteit hebben, maar we hebben wel groene waterstof.

In de staal industrie zijn ook veranderingen bezig. JO verwacht er steeds betere manieren komen om staal te hergebruiken, wat leidt tot een afname in de behoefte om nieuw staal te produceren, dus ook minder kooks. Als het overige deel van de staal behoefte nog steeds via het kooksproces wordt geproduceerd en er is geen andere manier, dan moet je zo efficiënt mogelijk met die achterkant omgaan. Als nou blijkt dat je die waterstof er uit kan halen en die in mobiliteit kan stoppen waar geen extra emissie wordt veroorzaakt (inplaats van naar gascentrale waar elektriciteit wordt gemaakt en CO2 bij vrij komt) is het een waardevolle bijdrage. Zeker als we overgaan op waterstof als energiedrager. Dan ga je namelijk niet de waterstof verbranden, wat een slechte efficiëntie heeft, omdat je het verbrand en er komt veel warmte bij vrij waar je niks aan hebt. Daarom was de oorspronkelijke gedachte van BMW om waterstof in een verbrandingsmotor te gaan gebruiken een slecht idee door lage efficiëntie van die proces.

*Zou je er op dit moment van de transitie je geld op zetten?*

Nee, omdat wij op dit moment die grote hoeveelheid waterstof nog niet nodig hebben. Bovendien is er genoeg waterstof beschikbaar met de juiste karakteristieken om het werk binnen de transitie te doen. Dan zou ik de afvalstromen verder verwerken zoals je nu ook doet (Nuon, verwarming).

*Welk stadium zou je dit als interessante optie beschouwen?*

Ik denk pas na 2035. Als we de transitie inzetten komen er vanaf dat moment geen voertuigen meer op de weg die uitstoten, dan zullen er dergelijke grote hoeveelheden waterstof nodig zijn.

*Maar zijn tegen die tijd niet de electrolyzers voldoende geëvolueerd en kost-efficient genoeg?*

Ik verwacht niet dat de electrolyzers zo snel veel beter worden. Wat ik wel verwacht is dat er op een gegeven moment zoveel zon en wind is, dat efficiëntie ook niet meer relevant is. Ik heb in 2012 meegewerkt aan scenario's, waarbij we 1 scenario hebben bekeken waarin energie geen beperking meer is. Als energie geen beperking meer is hebben we geen oorlogen meer, dan hebben we geen geopolitieke discussies over grondstoffen meer, overal kan je dan ter wereld zoet water maken dus dat ook geen issue meer. Als energie geen issue meer is krijg je een drastisch andere samenleving. Efficiëntie dus geen obstakel. Dan is de driver puur economisch (kunnen we het met acht electrolyzers doen in plaats van 10).

Fuel cells zijn momenteel bovendien al behoorlijk efficiënt. Zo ook de omgekeerde route om uit waterstof en zuurstof elektriciteit te maken.

Het punt met bij-product waterstof uit kooksofengas is dus dat er al een behoorlijke hoeveelheid waterstof aanwezig is die ook nog eens voldoet aan de groene certificering (of carbon free definitie). Dat betekent dus dat het erg lastig wordt (voor tata) om in die markt te treden met waterstof die ook nog eens niet carbon free is.

*Maar er is toch geen andere bron van waterstof in Noord-Holland?*

Nee maar je moet naar de totaaleconomie kijken. Dan moet je afwegen of je het bij tata comprimeerd en in een tube trailer stopt of Air Liquide doet het in Antwerpen, dan kunnen zij het goedkoper.

*Hoe dan?*

Omdat ons waterstof veel efficiënter geproduceerd wordt. De kosten zitten niet in de 20 km die Air Liquide verder moet rijden, maar in de compressie en vullen van de tube trailers, het weer leeg maken en überhaupt het hebben van die trailers. Die trailers rij je naar het vulpunt, die zet je neer en worden daar geleegd en worden steeds omgewisseld. Er zit dus ook een grote investering in trailers. Die heeft Air Liquide dus ook. Dit zijn dus marginale kosten voor zo'n bedrijf. Het wordt dus heel lastig om te concurreren met de gasmarkt.

*Maar dat zou ook niet de invalshoek zijn. Je zou eerder zeggen, wij hebben een potentiële voorraad waterstof, is er een samenwerking mogelijk met een gasbedrijf?*

Dat begrijp ik. Maar wij hebben al een heel efficiënt proces waarin ik waterstof produceer. Wat betreft dat kooksofengas hebben wij voldoende ervaring met diverse soorten gassen, dus kooksofengas zouden wij ook naar kunnen kijken. Maar dan gaan we gewoon concurreren: dit is het rendement wat we uit deze waterstof halen en vergelijken. Plus het feit dat we daar niet het label "carbon free" op kunnen plakken.

*Laatste vraag: stel je zou ondanks alles toch een cluster voor waterstof willen bouwen in region NH, wat zou je dan doen?*

Eerste afbakenen: van buiten Noord-Holland mag je niet naar binnen met waterstof.

Ik ken een andere casus waarbij een product vanuit Gouda naar Mijndrecht getransporteerd moest worden, maar dat kon niet want de provincie wilde niet mee.

Het is dus ten eerste vooral een kwestie van zo goed mogelijk aan het voetlicht krijgen bij politici en ambtenaren van de provincie en stadsregio Amsterdam en van NV Schiphol: Dat dit de weg naar zero-emissie is gelieerd aan de doelstellingen 2035/2050. Dat traject bewandelen en zeggen, dit kan met waterstof vanuit hoogovens omdat daar een bron ligt. Je kan ook aangeven dat op het moment dat de infrastructuur er is dat je dan over kan op andere groene bronnen. Je hebt namelijk in

Noord-holland aan de kust windparken die een potentiële bron zijn van groene stroom voor electrolyse. Dit op termijn, ook met oog op de mogelijkheid dat de staalproductie achteruit gaat en er minder nieuw staal nodig is. De infrastructuur zal dan dus gevuld kunnen worden met op den duur met groen waterstof vanuit een andere bron. Dit kan ook een transitie zijn, waarbij je geleidelijk de bij-product waterstof gaat vervangen door groen waterstof uit electrolyse. Op deze manier heb je dus ook een sustainable waterstofeconomie met ook op de vraag: Wat als Tata straks weg is en er is geen waterstof voorziening na het aanleggen van de heel infrastructuur? Soort back-up plan, want je kan niet gokken op een particuliere onderneming die zomaar kan stoppen.

Dan heb je ook meteen de volgende vraag beantwoord die vanuit de politiek wordt gesteld: “hoe groen is dat dan?” Hiermee vermijd je namelijk dat je waterstof hoeft te verstoken in een gascentrale. Door de waterstof eruit te halen vermijd je electriciteitsproductie uit gas. Ik moet van het gas af dus ik moet er elektriciteit van maken (alternatief is fakkelen?). En op termijn past dit in die transitie waarbij je als NH van de infrastructuur blijft gebruiken maar dan met een andere (groenere) bron.

*Meeting National Hydrogen Platform, Task Group buses 19-05-2016'*

*Date: 19<sup>th</sup> of May, 2016*

*Attendees:*

*Twysntra Gudde, REBEL consultancy, Holthausen, Hymove, Ministry of Infrastructure and environment, Connexxion, delegates from the provinces of Groningen, Gelderland, Noord Brabant, Rotterdam, Stedin, van Hool*

.....

Elk jaar is er een call vanuit de EU voor consortia vorming voor subsidie. Hier is lobbyen voor nodig. Nederland staat klaar voor opschaling van waterstof. FCH JU eist betrouwbaarheid. Daarom letter of intent geëist. Ook van vervoerders en vanuit regio's.

Momenteel is er een pilot in Rotterdam van RET met twee waterstofbussen.

Project: Hydrogen nodes EU wordt genoemd

2 bussen pilot Groningen

De call voor 2017 is in de lobby fase.

Clustermanagers/coördinatoren hebben als rol om te lobbyen bij overheden en gaan achter middelen aan die nodig zijn. Goede consortia aanvragen zijn moeilijk gebleven, vandaar dat FCHJU een 'template' stuurt om initiatieven een hand te helpen.

Subsidie: 2ton per bus en 1,2 miljoen bijdrage aan tankstation

Verschil tussen subsidie middelen en garantiemiddelen. Garantiemiddelen dragen bij aan de mogelijkheden maar moeten worden terugbetaald.

Er wordt ook gekeken naar waterstof treinen in de toekomst.

Er zit minimaal een jaar tussen aanvragen van een voertuig en het daadwerkelijk inzetten van een voertuig, vandaar tijdig beginnen met aanvraag.

IPO akkoord wordt genoemd

VanHool produceert waterstofbussen (maakindustrie), en kan 45 bussen leveren per jaar.

Ten T dagen komen er aan, algemene agenda online te vinden, velen zullen aanwezig zijn. Dit project gaat puur over realisatie van infrastructuur voor mobiliteit.

Onduidelijk of connexion of regio's zich hebben teruggetrokken uit pilots, ontstaat discussie.

Vertrouwen is zeer belangrijk!

Deadline voor calls EU eind van het jaar, dus 31-12-2016 deadline voor 2017.

Jan Willem de Kleuver, IenM en onderdeel clustermanagement.

Concessies ivm met transitie eenmalig voor 15 jaar, schept vertrouwen en verlaagt risico.

Hymove momenteel bezig met pilot voor een 12 meter bus. Actieradius 450-500 km, 30kg waterstof , rijdt 15 km op 1kg. Worden van alle kanten benaderd door bedrijven, niet alleen bussen maar ook boten, trucks etc. Groeiende belangstelling dus.

Waterstofnet is een Belgische stichting zonder winstoogmerk. Zullen niet toeleggen op langetermijn projecten met hoge investeringen.

NWP heeft 2 financieringsstromen: privaat / publiek. Ministerie IenM heeft deel toegezegd voor dit jaar. Federatie mobiliteitsbedrijf NL en Shell worden benaderd.

Volgende meeting: maandag 13 juni van 10-12

Verder: Erik Buthker van Pitpoint bekende van Gerard Jägers, zouden graag een keer willen praten.

Schiphol maakt het mogelijk dat anderen het werk kunnen doen. Luchtvaartmaatschappijen maken gebruik van start en landingsbanen, Schiphol onderhoudt het, sloopt het etc. Het parkeren van vliegtuigen gebeurt op platformen die Schiphol beheert, onderhoudt inspecteren. Gebouwen zijn ook van schiphol, mensen die daar werken betalen huur aan Schiphol. Eigenlijk dus meer een infrastructuur en vastgoed bedrijf dan een operator.

Operators zijn luchtvaartmaatschappijen en in kader van brandstof afhandelingsbedrijven - die zorgen voor vliegtuigen klaar gemaakt worden voor vertrek, en allerlei voertuigen bij betrokken als tankwagens, waterwagens, wc wagens bagagekarren, vrachtrekkers etc. Vervoer en werktuigvoertuigen die niet van Schiphol zijn maar van andere bedrijven. KLM is bv ook een grote afhandelingsbedrijf.

Bussen heeft Schiphol wel zelf, maar alleen die op het platform zelf rijden. Zijn inmiddels allemaal elektrisch.

Taxi's zijn niet van Schiphol maar van taxi bedrijven – gebruik vaak de naam om klanten aan te trekken. Deze bedrijven hebben een concessie gekregen van Schiphol om daar te mogen rijden. De huidige concessie was er al, the GROUNDS heeft er aan toegevoegd dat er ook op het gebied van duurzaamheid eisen worden gesteld. Eens in de acht jaar wordt de concessie getenderd.

Dit is om even het beeld te schetsen. Als je rondom Schiphol wat voor elkaar wil krijgen wordt je ontzettend veel doorverwezen naar verschillende bedrijven. Schiphol fungeert als regisseur.

Gemeenschappelijk noemer is dat alle partijen die rondom Schiphol opereren hebben allemaal iets met duurzaamheid te maken. Niet alleen over CO2. Grootste factor is luchtkwaliteit: NOx, fijnstof, etc. Daar is veel in te doen. Met name luchtkwaliteit waarmee mensen elke dag te maken hebben of deze verbeterd kan worden.

*Hebben deze bedrijven dit ook in hun bedrijfstrategie verweven?*

Weet ik niet. Ze roepen het wel allemaal, maar of ze er geld voor over hebben is maar de vraag. Twijfelt Ed over hoe het echt beleefd wordt.

Kansen genoeg, met name voor waterstof. Waterstof moet dan wel concurreren met andere bronnen van energie zoals accu's. Momenteel is er een meerjaren project

gaande om zoveel mogelijk equipment met name op air side om die elektrisch te maken met accu's. Loopt goed. Voertuigen die afgeschreven zijn worden vervangen door voertuigen met een accu, maar dan is het meteen de vraag waar die geladen kunnen worden. Hoe snel wordt die infrastructuur dan gebouwd? Schiphol is de infrastructuur provider dus verantwoordelijk voor alles wat aan de grond genageld wordt - zorgen dat er stroomkabels liggen, laadpalen op de goede plek. Alles wat niet aan de grond genageld is is van derde partijen. Schiphol heeft wel een aantal brandweer auto's. Ground Power Unit's zijn van luchtvaartmaatschappijen, tenzij ze vast aan de grond genageld zijn.

Alles wat wielen heeft is momenteel gericht op electrificatie. Het beleid is "electrisch, tenzij..". "Tenzij" heeft invloed op vermogen wat een voertuig heeft, bedrijfstijd, veiligheid, kosten. Ed heeft een aantal keer gesproken met baas van tankwagens: "op het moment dat er een tankwagen op waterstof op de markt komt ben ik de eerste die hem koopt.". Het personeel klaagt constant of de dieseldamp, die motor die draait, die pomp moet draaien. En die dingen gaan 20-25 jaar mee.

Afhandelaren staan constant onder druk van kosten staat – heeft erg weinig ruimte om te investeren. Harde concurrentie, worden uitgeknepen. Denken dus wel drie keer na voordat ze iets extra's doen. Kijken vaak naar Schiphol met als argument "Schiphol is toch degene die luchtkwaliteit wil", Schiphol antwoord niet verantwoordelijk te zijn voor uitstoot, dat zijn de afhandelaren met stinkende trekkers. Schiphol kan erop aangesproken worden, maar het enige wat zij kunnen doen is andere partijen vragen of ze mee willen doen. Het speelveld is er een waar het zeer lastig onderhandelen is.

Is een tankboot mogelijk via het Noordzeekanaal? Van Tata naar Schiphol.

Ed Koelemijer: los van kosten en techniek zit er ook een stuk emotie bij. Er hoeft maar 1 hoge boom tegen waterstof te zijn en het plan gaat niet door.

*Heb je ervaring met weerstand (emotie)?*

Ja. Meestal bij de safety/security mensen. Is generiek, niet bij bepaalde toepassingen. Wat Ed vaak hoort is dat als Waterstof tanks bij vliegtuigen in de buurt komen is het gevaarlijk, is volgens hem geen argument. Airbus is bezig om waterstof in het vliegtuig te krijgen.

For the time being is alles gericht op elektrisch, contract loop over 6 jaar af. Geldt alleen voor taxi's die onder de concessies rijden – dus aankomende passagiers. Je komt alleen het platform (slagboom door) als je een concessie hebt. Die concessie houder heeft afgesproken dat hij met een elektrische taxi komt. Het moet aantrekkelijk zijn voor een taxi bedrijf om met een electische of waterstof taxi te gaan rijden. Het gros van de markt wordt geregeld door gerenommeerde taxi bedrijven, komt neer op 80-90%. The Grounds heeft in de tender aangegeven: je krijg 40 punten van de 100 (aan eisenpakket voor tender) voor zero-emissie.

Op het platform wordt met gemiddeld 40 bussen gereden. Zijn korte afstanden, dus niet aantrekkelijk voor waterstof. Overig vervoer wordt geregeld door de regio. Wordt ook regelmatig getenderd, is aan de regio. Komt er binnenkort aan. Er zit veel weerstand bij vervoersbedrijven – exploitatie gaat omhoog van de bussen etc. Terwijl landelijk wordt gezegd dat we naar zero-emissie moeten. Of het tarief van het openbaar vervoer moet omhoog of er moet meer subsidie bij, anders is het niet mogelijk.

De overheid zit ook met de handen in het haar. Als ik de overheid was zou ik zeggen; iedere tender die nu uitgeschreven wordt komt zero-emissie in. Kan je altijd nog besluiten dat als het leidt tot abnormaal hoge kosten doe je het niet. Zo kan je het omdraaien. “Zero-emissie, tenzij”. Toen dat voor geschreven werd voor de taxi's stond de telefoon roodgloeiend, wat voor idioot Ed Koelemeijer wel niet was om dat voor te schrijven. Veel weerstand voor de “40 punten voor zero-emissie”. Waarom niet? Gaan ze niet doen! Zien we dan wel, zegt Ed. Ed had mazzel, Tesla net begonnen met fabriek in Tilburg, heftig op zoek naar markt. Geen euro korting. Dat gaat zingen, dan wil iedereen korting. Mercedes etc wilde wel korting geven.

Bij bussen is het hetzelfde verhaal. Europese tender uitgeschreven, zero-emissie voorgeschreven. Hoeveel personen erin moeten kunnen etc. Iets minder dan 40, rond de 30. Dit is Europees aanbesteed. Die is gewonnen door de Chinezen, Build Your Dreams had net een Europese vestiging.

Vantevoren heeft Schiphol de kans gegeven om de bussen proef te draaien. Daar kwam alleen die Chinezen op af. Stadsbussen die al in China reden hebben ze op de boot gezet. VDL kwam na dit nieuws verschrikkelijk boos op Schiphol dat zij niet de Nederlandse markt stimuleerde. Was wel 13 miljoen duurder en had nog geen bus. Dan krijg je een prototype daar rondrijden. Ze worden nu wel wakker geschud. VDL is een echte kilo knaller. Je moet de markt wakker maken door volume neer te zetten. Als KLM heeft al jaren goed contact met Harlan, gaan zeer familiair met elkaar kom.

*Waar zit het echte volume dan?*

Dat zit bij vehicles met hoog vermogen en lang bedrijfstijd. Bussen, tankwagens, GPU's, vrachttrekkers, dus echt het zware equipment. Op termijn de vliegtuigen zelf. Iedereen heeft het nog altijd over het kop en ei verhaal. Wij willen wel op waterstof gaan rijden, maar Schiphol – gaan jullie nog een tankstation bouwen? KLM heeft zijn eigen stations.

*Wat is de rol van schiphol bij het bouwen van waterstof infra?*

Alleen grond beschikbaar stellen. Schiphol zou geen station bouwen. Schiphol heeft veel moeite om ontheffing te houden voor een eigen nutsbedrijf. Liander en Alliander zit in ons nek, claimen dat het een dorp is met een waar kabels die moeten worden aangelegd etc .... Het is erg duur om een eigen netwerk te hebben. Met name door

organisatie - mensen moeten opgeleid worden, wordt steeds moeilijker om vol te houden. Brandstofleiding is ook niet van Schiphol voor kerosine. Zijn van Aircraft fuel supply? In samenwerking met brandstofmaatschappijen. Schiphol zorgt alleen dat het mogelijk is, ga de markt maar opzoeken.

*Als er een waterstof cluster wordt gevormd, wat is de rol van Schiphol dan?*

Hoeft alleen bij opstartfase aan tafel, daarna kan de markt het zelf regelen. Voor besluiten zoals voor veiligheid moeten zij ook naar de gemeente. Gemeente is verantwoordelijk voor de veiligheid.

Heel goed om inzichtelijk te maken: Wie heeft welke rol?

Breedenoort: Heeft al een waterstof aangedreven aggregaat.

Bij het bouwen van infrastructuur voor wet

Je zit momenteel met die accu's, dat gaat wel goed.

*Waar zitten de sparks?*

- 1) Eerste toepassing moet er zijn. Als Frankfurt over gaat op waterstoftoepassingen, Schiphol mee?
- 2) Als het lukt met een bepaald stuk equipment, is het eerste schaapje over de dam. Als die lukt gaat het rollen.
- 3) Toch top-down draagvlak creëren.
- 4) Beetje een doodoener, maar toch subsidie. Eigenlijk meer een randvoorwaarde
- 5) Eerste toepassingen kunnen ook van buitenaf komen.

